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DARK INCLUSIONS IN A TONALITE OF SOUTHERN CALIFORNIA*

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Dark inclusions in granitic rocks have long been a source of controversy, and it was with the hope of shedding light on the mooted question of their origin that the present inquiry was undertaken. While mapping the petrology of the San Luis Rey quadrangle in Southern California, Professor E. S. Larsen realized the suitability of that area for a study of inclusions. With the aid of his excellent map of the various bodies of intricate pattern, the work was greatly facilitated.

Utmost thanks are due to Professor Larsen for his helpful advice in both field and laboratory, and to Professor Charles Palache for a generous grant for field expenses from the Holden Fund of the Department of Mineralogy of Harvard University.

The Peninsular Range of Southern California is made up largely of a composite batholith of Jurassic age intruded into schists and quartzites that are metamorphosed and folded Triassic sedimentary rocks. The succession of intrusions has proceeded in the normal order with gabbro followed by increasingly more silicic rocks. The first intrusive is locally called the San Marcos Mountain gabbro, and is followed by a quartz diorite known as the Bonsall tonalite. Several more silicic rocks followed the tonalite. Although inclusions are to be found in all the rocks of this igneous sequence, the Bonsall tonalite carries them most abundantly, and, consequently, work was largely confined to this body.

THE SAN MARCOS MOUNTAIN GABBRO

Since in the opinion of the writer, most of the inclusions of the Bonsall tonalite were derived from the San Marcos Mountain gabbro, it seems well to preface the discussion of inclusions with a brief statement concerning the gabbro.

* A portion of a thesis submitted to Harvard University in partial fulfillment of the requirements of the doctorate.

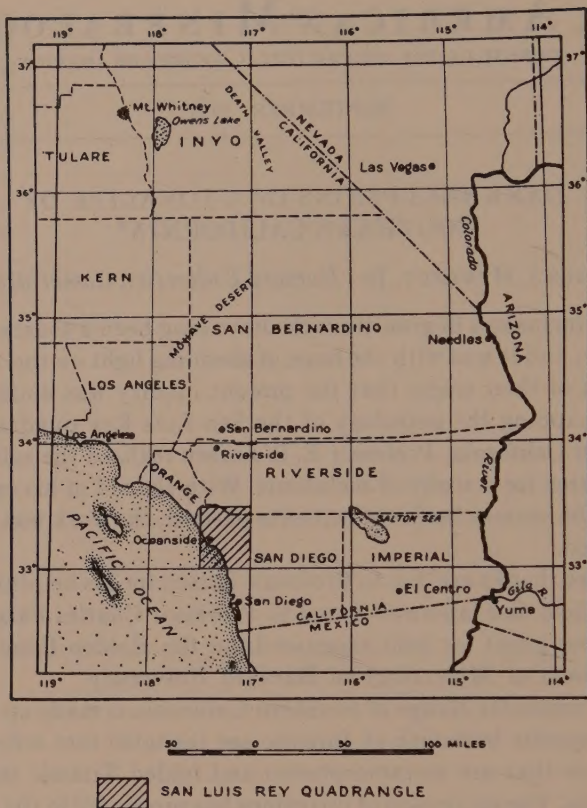


FIG. 1. Location of the San Luis Rey quadrangle.

According to Miller,¹ "The typical San Marcos Mountain gabbro is a medium-grained, dark gray, plutonic rock composed essentially of plagioclase feldspar and pyroxene. More or less uraltic hornblende is usually present." In some localities the pyroxene has been nearly completely altered to hornblende, and in these cases the large hornblende crystals poikilitically inclose the other mineral constituents.

Miller recognized three types of gabbro depending on the presence of minor constituents. These types are: first, the true gabbro carrying only pyroxene and hornblende as dark minerals; second,

¹ Miller, F. S., *Petrology of the San Marcos Mountain Gabbro, San Luis Rey Quadrangle, California: Thesis, Ph.D. Harvard University, 1934.*

gabbro carrying quartz and biotite; and, third, gabbro in which olivine occurs to the exclusion of quartz and biotite. Labradorite feldspar is the most abundant constituent of all the types. However, in the olivine-bearing rocks, the labradorite carries cores that have a composition between bytownite and anorthite. Frequently this calcic feldspar is present to the exclusion of the labradorite.

THE BONSTALL TONALITE

The Bonsall tonalite derives its name from the small village of Bonsall located slightly west of the central portion of the San Luis Rey quadrangle. Its boundaries, like those of the other igneous bodies of the area, are extremely irregular. Altogether the Bonsall tonalite underlies approximately one hundred square miles in the San Luis Rey quadrangle, thus making it the largest single unit of plutonic rock.

MARGINAL ASSIMILATION. Field evidence in several instances points to the fact that the original differences in composition of the Bonsall tonalite have been emphasized locally by marginal assimilation at the contact of the San Marcos Mountain gabbro. On the geologic map of the San Luis Rey quadrangle, these two rocks are shown in contact with one another for several miles, but, in spite of this fact, it is impossible to trace the contact for even one hundred yards. The reason for this is that there is apparently no true contact between the two.

However, there are places where one can cross from one body to the other and continue to observe bed rock. If at one of these favored localities a traverse is made from tonalite to gabbro, the rock gradually becomes increasingly darker. One may start in rock that is unquestionably tonalite and as it gets darker it still retains the properties of the tonalite, but at the same time begins to resemble the gabbro. Over a distance of several hundred yards, therefore, there is a transition zone of intermediate rock, a hybrid, having been formed by the union of the two major intrusives. Such a complete gradation as exists points to a mutual assimilation. It seems not beyond the realm of possibility to postulate that after the gabbro had attained its present position in the earth's crust, but before it was completely solidified, the Bonsall tonalite was intruded. With one rock in a semi-solidified condition, and the other in a molten state a certain amount of mechanical commingling could take place with subsequent diffusion and chemical reaction.

Such a set of conditions one would expect to give rise to a hybrid rock at the contact of the two intrusives.

Conditions similar to these just noted are not uncommon in the literature. Harker² described hybrid rocks from Scotland formed in a similar manner. Likewise, Clapp³ has attributed the origin of essexite to the commingling of two magmas. Goodspeed⁴ also describes satellitic phases of a granite mass in Oregon due wholly or in part to hybridism. Other examples are common, and the amount of hybrid rock formed in most instances is considerably more than in the case under discussion.

PETROGRAPHIC DESCRIPTION. The Bonsall tonalite is a medium-grained plutonic rock presenting in the outcrop a color of varying shades of gray which distinguishes it in the field from the other intrusives. When examined under the microscope, this rock shows a considerable variation in the relative proportions of its mineral constituents. Nevertheless, the composition does not vary between wide enough limits to permit many specimens to fall outside the restricted range of tonalite.

Zoned plagioclase, in thin tabular grains flattened parallel to (010) and slightly elongated along the *a*-axis, makes up at most localities well over 50% of the rock. Its average composition varies from An₃₂ to An₄₉, but is usually about An₄₀. Quartz and orthoclase are interstitial to the plagioclase and dark minerals. The former makes up from 20% to 25% of the rock, while the latter in most places makes up less than 5%. At one locality, however, a light-colored tonalite carries 15% orthoclase. Hornblende and biotite each make up about 10% of the average rock. Their range in optical properties are:

	<i>Hornblende</i>	<i>Biotite</i>
Sign	(—)	(—)
2V	60°–75°	0°–5°
Orientation	$Y=b, Z \wedge c \ 20^{\circ}\text{--}27^{\circ}$	$Y=b, X \wedge c \ 2^{\circ}$
Dispersion	$r > v$	
Pleochroism	X =pale yellow Y =olive green Z =deep green	
Indices	α =1.651–1.671 β =1.663–1.683 γ =1.673–1.690	α =1.605–1.625 β and γ =1.642–1.661

² Harker, Alfred, *The Natural History of Igneous Rocks*, New York, 1909.

³ Clapp, C. H., *Geology of the Igneous Rocks of Essex County, Massachusetts: U. S. Geol. Survey, Bull.* vol. 704, 1921.

⁴ Goodspeed, G. E., *Recrystallization of Xenoliths at Cornucopia, Oregon: Bull. Geol. Soc. Am.*, vol. 42, 1931.

The above data indicate a maximum difference in the proportion of the iron and magnesia end members of about 20% for the amphibole, and less than 15% for the biotite.

Pyroxene is a mineral absent from the Bonsall tonalite except at those places where there is a transition into the older gabbro. Here it is obvious that the pyroxene has been contributed to the hybrid rock by the gabbro.

CHEMICAL COMPOSITION. Two chemical analyses of the Bonsall tonalite were made, the results of which are given below. Analysis A is of rock that can be considered typical, and came from a locality two miles northeast of the San Luis Rey Mission. Analysis B is that of a light-colored tonalite that represents the most extreme silicic variation.

CHEMICAL ANALYSES,* NORMS AND MODES OF
THE BONSCALL TONALITE

	Chemical analyses	
	A	B
SiO ₂	64.86	71.06
TiO ₂	0.55	0.56
Al ₂ O ₃	17.46	14.52
Fe ₂ O ₃	1.80	1.39
FeO	2.80	1.93
MnO	0.30	0.02
MgO	1.36	0.36
CaO	5.26	3.10
Na ₂ O	3.38	3.39
K ₂ O	1.64	3.08
H ₂ O	0.50	0.34
P ₂ O ₅	0.05	0.03
	<hr/> 99.96	<hr/> 99.68

* Analyses were made by F. A. Gonyer.

Norms			Modes		
	A	B		A	B
Quartz	24.36%	31.74%	Quartz	26%	30%
Orthoclase	9.45	18.35	Orthoclase	4	15
Albite	28.82	28.82	Plagioclase	51 An ₄₁	40 An ₃₂
Anorthite	26.13	15.01	Biotite	13	7
Corundum	0.61	—	Hornblende	6	8
Hypersthene	6.17	2.22			
Magnetite	2.55	2.09			
Ilmenite	1.06	1.06			
	<hr/> 99.15	<hr/> 99.29			

INCLUSIONS IN THE BONSALE TONALITE

NOMENCLATURE. Because of the widespread distribution of dark inclusions in granitic rocks, much has been written in recent years of their occurrence in various parts of the world. As a result, many terms have been introduced to denote various types observed by different investigators. Lacroix⁵ was the first to make a formal classification and assign various names to those formed in different ways. However, few words have been introduced into the English literature that correspond to Lacroix's terms, and, due to the different English connotation, his cannot be taken directly.

Several English terms have been suggested to apply to specific types of inclusions. In 1900 Holland⁶ proposed the term "autolith" to be applied to well-formed inclusions that have had their origin within the magma in contradistinction to xenolith or fragment foreign to the rock. "Basic concretion," and "basic segregation" have also been suggested, but their genetic implications, as in the case of autolith, prevent their general use.

In the present discussion, therefore, because of the short-comings of other words proposed, *inclusion* with necessary modifiers will be used. In the following pages "reaction inclusion" will be used in referring to the most abundant type in the Bonsale tonalite. The term is not considered a particularly suitable one, but it does convey the idea that is brought out in the following discussion; namely, that the inclusions are not segregations, but are foreign material and owe their present condition to reaction with the magma.

SPACE RELATIONS OF THE INCLUSIONS. Although the number of reaction inclusions is fairly uniform throughout the tonalite, there is a considerable variation in their abundance locally. At some places there are patches embracing a few square yards where the included material may make up as much as 30% of the volume of the rock, while at other places inclusions may be almost entirely wanting. It is seldom, however, that one finds even a single exposure without a few. Figure 2 shows the appearance of outcrops where inclusions are rather abundant. The large number of them is likely to lead one to over-estimate their volume percentage of the rock. The inclusions in figure 2A were found to make up 8%, and those in figure 2B 10% of the rock by volume.

⁵ Lacroix, A., *La Montagne Pelee et ses Eruptions*, Paris, 1904.

⁶ Holland, Sir Thomas, *The Charnockite Series: Mem. Geol. Survey India*, vol. 28, pp. 212-219, 1900.

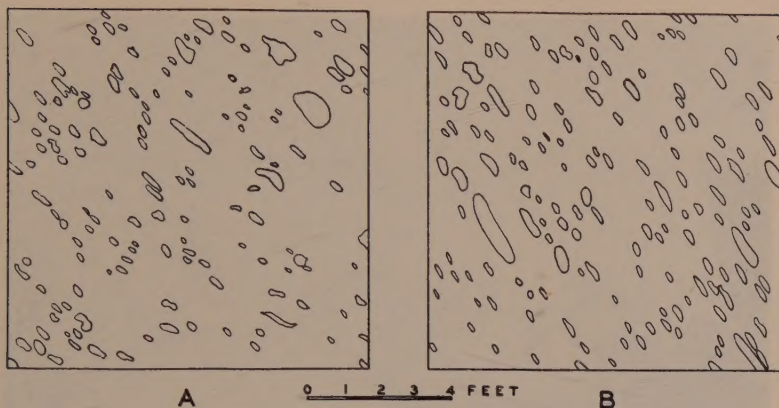


FIG. 2. Appearance of outcrops of Bonsall tonalite with abundant reaction inclusions.

The reaction inclusions show a rather small variation in size as will be seen from figure 2. The maximum dimension is, in general, from ten to twelve inches, but in extreme cases reaches as high as twenty-four inches or as low as one. However, because of the variation in shape, it is the volume rather than maximum dimension that should be considered in comparing inclusions.

SHAPE AND RELATION TO ROCK STRUCTURE. The shape of the reaction inclusions varies from a form approximating a sphere to a much flattened ellipsoid of revolution. If flattened inclusions are exposed on a surface cutting their long dimension, they appear as long narrow strips ranging up to two feet in length and down to $\frac{1}{4}$ inch in width; if exposed on a surface parallel to their long dimension, they appear as large disks with rounded outline. Moreover, wherever reaction inclusions are flattened, they show a nearly perfect parallelism, with the individual rarely varying more than a few degrees from the general strike. Not only do the inclusions show a parallel orientation, but the tabular and elongated minerals of the host rock, especially feldspar and hornblende, possess a definite alignment giving the rock a decided flow structure.

This flow structure is, in general, well marked throughout the whole mass of Bonsall tonalite, but locally becomes very poor and in places is entirely lacking. The reaction inclusions at such localities show no orientation, and are more or less rounded and equidimensional. Their shape, therefore, is closely related to the flow struc-



FIG. 3. A boulder of Bonsall tonalite showing on one face the streaked nature of the reaction inclusions; and on the other face, at right angles, the flattened character.

ture, which in turn represents the relative amount of movement of the magma.

The flattened nature of the inclusions where the movement has been great and the spheroidal character where movement was small or lacking point rather definitely to the fact that the inclusions were not rigid bodies, but must have been plastic during the emplacement of the rock. Good evidence of the plastic nature of the reaction inclusions, during at least the final movement of the magma, is shown at a locality where flow structure is pronounced and the inclusions greatly flattened. The flow structure, that is unusually constant in its direction, turns to bend around a large quartzite xenolith; and a tabular inclusion that lies within a few inches of the xenolith likewise bends to faithfully follow the flow lines.

STREAKING AND ITS RELATION TO REACTION INCLUSIONS. Not infrequently throughout the tonalite where there has been considerable movement there are streaks of dark rock alternating with lighter ones. There seems to be fairly good proof that these streaks are genetically related to the inclusions. The best evidence pointing



FIG. 4. A reaction inclusion being drawn out into a streak.

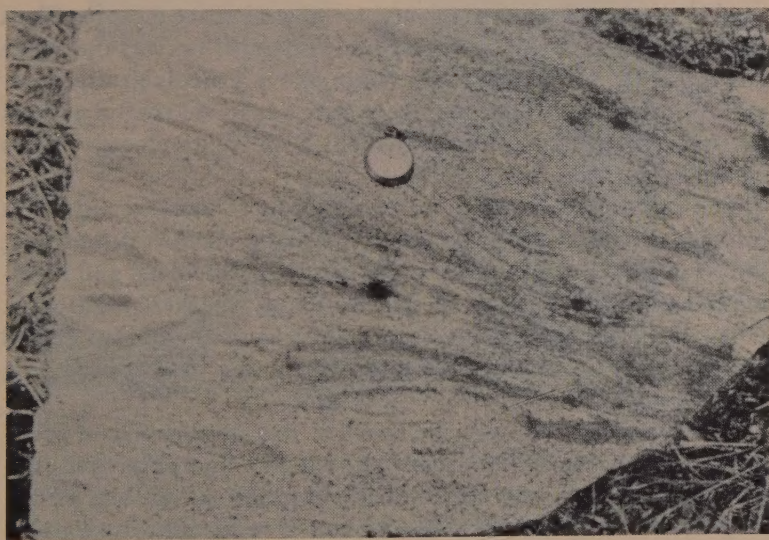


FIG. 5. Reaction inclusions being drawn out, and merging to form long streaks.

in this direction is the nature of some of the inclusions themselves, for not infrequently a definite inclusion can be found grading into or being drawn out into a streak. Where streaking is well developed, very few, if any inclusions are present, which points to the fact that inclusions that were there have been drawn out to form the dark streaks.

Another line of evidence substantiating the belief that the streaking is formed from inclusions is the very nature of the material itself. The texture of the inclusions is characteristic, being much finer and more compact than that of the host rock. Likewise, the mineral composition differs from that of the tonalite. Both of these properties are preserved to a large extent in the dark streaks. Thus streaking, as well as the flattening of inclusions, indicates that the plastic nature was acquired after the included material reached essentially its present location in the rock mass, and the last movement of the magma is recorded in its shape. If the inclusions were plastic during much movement, they would have undoubtedly lost their identity.

REGIONAL STRUCTURE. By means of the well-oriented minerals and inclusions in the Bonsall tonalite, the regional structure of the whole mass was determined. The method employed by Cloos⁷ was used in part but not in its entirety, for several of the features Cloos deems necessary were not found everywhere. However, the strike and dip of the plane of flow was taken on every available exposure, and the results are plotted in figure 6. It was found that in general the strike of the flow structure is about N 65° W, but locally varies considerably from this direction.

The attitude of the plane of flow is in most cases vertical, but occasionally dips slightly to the south. This northwest-southeast direction corresponds closely to the strike of the folded and metamorphosed Triassic rocks of this section of Southern California. It may well be that the northeast-southwest pressure that caused this folding was not completely relieved at the time of intrusion, but governed the movement of the magma.

It is interesting to note the effect of the older bodies of schist and gabbro on the direction taken by the flow lines. The best illustration of this is shown toward the eastern edge of the map. Here a long narrow strip of schist extends for several miles in approxi-

⁷ Cloos, H., *Tektonik und Magma*, Band I, 1922; Band II, 1924; Band III, 1927, *Abh. d. Pr. Geol. Landesanst. H. F.*, vol. 89, Berlin.

mately a north-south direction. The flow lines of the tonalite on both sides of the strip of schist turn to parallel faithfully the contact.



FIG. 6. The structure of the Bonsall tonalite.

PETROGRAPHIC DESCRIPTION OF THE REACTION INCLUSIONS.
The average inclusion of the reaction type presents in the hand specimen a dark gray to black color sharply contrasted with the light gray of the enclosing tonalite. The boundaries between the two appear sharp to the unaided eye, but with a hand lens an occa-

sional mineral grain can be seen to penetrate from the host into the inclusion. In a few cases, the contacts between the inclusion and tonalite are not sharp but show a gradual merging of the two. The texture of the inclusions is so fine grained that it is only with difficulty that one is able to distinguish individual minerals. However, hornblende, biotite, and occasionally feldspar are sometimes found in grains large enough to be recognized in the hand specimen.

Microscopically the reaction inclusions are all very similar to one another with a uniformly fine grain and hypidiomorphic texture. The principal minerals listed in the order of their abundance are: plagioclase, hornblende, biotite, quartz, orthoclase, and pyroxene. The first three make up the bulk of the inclusions and are present in all, while the last three are found only in small amounts and frequently may be lacking altogether.

Tabular plagioclase feldspar with a composition of about An_{45} is the chief constituent of the reaction inclusions. It is frequently zoned with only a small difference in composition between the core and rim, but occasionally the inner zone is found to be near the center of the labradorite group. One of the most outstanding features of the inclusions is the presence in many of them of zoned feldspar grains larger than the average with irregular and embayed cores with a composition of about An_{90} . These calcic cores are uniform in composition and sharply separated from the outer zones that are similar to the other feldspar. They are conspicuous in plane polarized light due to their high relief, and between crossed nicols due to their yellow interference color.

These conspicuously zoned feldspars are common constituents of many of the inclusions. In individual cases they may make up as much as 5% to 10% of the specimen, while in others they may be represented by one or two grains, or may be lacking altogether. Several scores of thin sections were examined that showed both the inclusion and the adjacent host rock; and, whenever this unusual type of feldspar was found, it was confined to the inclusion.

Both quartz and orthoclase are present in only small amounts in the reaction inclusions, and together rarely make up over 3 or 4%. They are invariably found together interstitial to the plagioclase and dark minerals.

Hornblende in small prismatic grains is the principal dark mineral of the reaction inclusions, and is present in amounts varying from 20% to 45%. In addition to these small prisms, there are fre-

quently larger anhedral grains that may inclose the feldspar poikilitically. Biotite is found in the inclusions in amounts varying from 10% to 20%. It is frequently found developing from the hornblende along cleavage planes, and in places completely surrounds it.

Considered from the standpoint of the amount present, pyroxene is one of the rarest minerals in the reaction inclusions, but, nevertheless, it has an important bearing on their origin. In the many thin sections examined, pyroxene was found in only a few. Both augite and hypersthene were present, and in all cases were altering to hornblende. These inclusions both mineralogically and texturally, aside from the small amounts of pyroxene, appear similar to the others; and, if the process of alteration had been complete, they would be identical.

Of the accessory minerals in the reaction inclusions, magnetite is most important and may make up as much as 3% of the rock. Titanite is frequently present in its characteristic wedge-shaped grains. Occasional grains of apatite, zircon, carbonate, allanite, and pyrite were observed, but are unimportant.

COMPARISON OF THE REACTION INCLUSIONS WITH THE BONSALE TONALITE

MINERAL COMPARISON. The foregoing petrographic descriptions of the inclusions and tonalite show that they are mineralogically very similar. Plagioclase feldspar, quartz, orthoclase, hornblende, and biotite in varying proportions are constituents of both. The chief variations in the mineral composition are shown in hornblende, biotite, and quartz, the dearth of quartz in the inclusions being balanced by an increase in the hornblende and biotite. Thus, the percentages of the other minerals remain nearly the same in both inclusions and host.

In order to compare the composition of the hornblende of the inclusions with that of the tonalite, the optical properties were determined on hornblende both from the inclusions and the adjacent rock. Determinations were made on specimens from ten separated localities to get a representative comparison. For all the hornblende the following properties were similar: Optically (-), $2V=60^{\circ}-75^{\circ}$, $r > v$; $Y=b$ =olive green, $Z \wedge c 20^{\circ}-27^{\circ}$ =deep green, X =pale yellow. The indices of refraction vary somewhat as shown on the next page.

INCLUSIONS	TONALITE
$\alpha=1.640-1.664$	$\alpha=1.651-1.671$
$\beta=1.652-1.669$	$\beta=1.663-1.683$
$\gamma=1.662-1.682$	$\gamma=1.673-1.690$

These data show a close relation between the various hornblendes, but indicate that the hornblendes of the inclusions are higher in magnesia and lower in iron than those of the tonalite.

A comparison of the optical properties of the biotite of host and inclusion showed in six out of ten specimens a higher refractive index of the biotite of the tonalite than for the corresponding inclusion. In the remaining four, the biotite of both gave the same refractive indices. Consequently, in the majority of specimens, the biotite of the tonalite is richer in iron than that of the inclusions.

A comparison of the plagioclase feldspar of the inclusions with that of the surrounding tonalite was made on the same specimens as the other mineral comparisons. The composition varied from place to place, but in all cases the feldspar of the inclusions, exclusive of the inner zones rich in anorthite, had essentially the same composition as that of the host rock immediately surrounding it.

ORIENTATION. In order to determine the extent to which mineral orientation was present in the inclusions and compare it with the orientation of the surrounding rock, especially cut thin sections were made. These sections were large enough to include portions of both the inclusion and adjoining tonalite, and were cut at right angles to the flow structure. The method used to orient the mineral grains was that developed by Schmidt and Sander⁸ with the use of the Fedorov stage. Each of the contour diagrams, figure 7, represents one mineral in either the inclusion or host rock. All of the counts were made on the same thin section, so that a direct comparison of corresponding minerals is possible.

Diagram A, figure 7, represents the plotting and contouring of 102 plagioclase feldspar grains of the tonalite, while diagram B is the same for 102 plagioclase grains of the inclusion. In both cases the pole of the side pinacoid was plotted, and a comparison of the two diagrams shows a similar orientation. Where possible the grains were further oriented by locating the trace of the basal cleavage. The feldspar grains thus completely oriented brought out the fact that there is not only a sub-parallel arrangement, but also the *a*-

⁸ Schmidt, Walter, *Tektonik und Verformungslehre*, Berlin, 1932; Sander, Bruno, *Gefugekunde der Gestein*, Vienna, 1930.

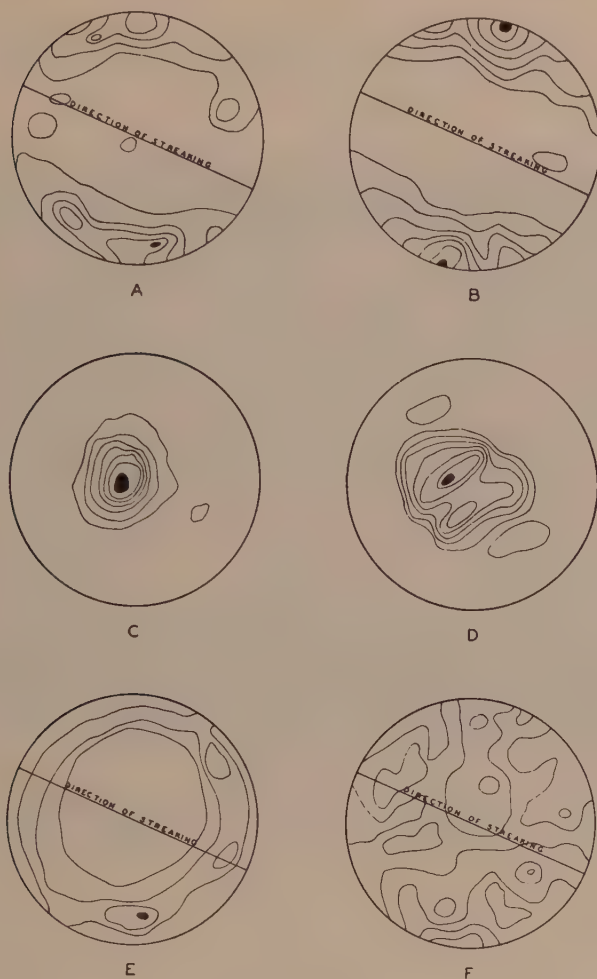


FIG. 7. The above diagrams are the contouring of the projections of minerals from both the tonalite and inclusion.

A. The poles to the (010) face of 102 feldspar grains of the tonalite. Contours equal 7-5, 4, 3, 2, and 1 per cent.

B. The poles to the (010) face of 102 feldspar grains of the inclusion. Contours equal 8-7, 6, 5, 4, 3, 2, and 1 per cent.

C. The *a*-axes of 102 feldspar grains of the inclusion. Contours equal 9-7, 6, 5, 4, 3, 2, and 1 per cent.

D. The *c*-axes of 119 hornblende grains of the inclusion. Contours equal 9-7, 6, 5, 4, 3, 2, and 1 per cent.

E. The *b*-axes of 119 hornblende grains of the inclusion. Contours equal 7-5, 4, 3, 2, and 1 per cent.

F. The *c*-axes of 130 quartz grains of the tonalite. Contours equal 3, 2, and 1 per cent.

axes tend to be aligned in a given direction. The *a*-axis is the direction of elongation, and diagram C brings out the rather perfect arrangement in a linear direction.



FIG. 8. A section across the flow structure of a flattened inclusion.

The directional orientation is brought out in a similar manner in the projection of 119 hornblende grains of the inclusion shown in diagram D, figure 7. Here the *c*-axes were plotted, and the grouping of the contours near the center of the diagram again indicates a linear orientation, for the hornblende is elongated parallel to the *c*-axis.

The hornblende grains were further oriented by plotting the *b*-axes. Here, as shown in diagram E, figure 7, there is no sub-parallel arrangement as in the case of the feldspar, for the hornblende grains are too equidimensional in the prism zone.

Diagram F, figure 7, is a projection of the *c*-axes of 130 quartz grains of the tonalite. The irregularity of the distribution of the contours shows at a glance that there is no systematic orientation. Since the quartz was the last mineral to form, one would not ex-

pect it to be oriented, for it crystallized after movement had ceased, and was not thus influenced by flow.

A comparison of diagrams A and B, figure 7, shows that a similar orientation of minerals is present in both the inclusions and tonalite but better developed in the inclusions. The rather perfect linear



FIG. 9. Photomicrograph of the contact shown megascopically in Fig. 8. This is a portion of the thin section on which the mineral counts recorded in Fig. 7. were made. Crossed nicols, $\times 15$.

orientation of the minerals of the inclusions was not discovered until field work was completed. It may be that the orientation is radial in each individual reaction inclusion, rather than there being a constant direction throughout. Additional work should be done to determine its exact nature.

THE ORIGIN OF INCLUSIONS

SUGGESTED METHODS. There have been several methods suggested by which inclusions comparable to those of the Bonsall

tonalite have originated. Chief of these, and apparently the most generally accepted, is that the inclusions are segregations or concretions rich in dark minerals, and that they and the rock surrounding them have come from a common magma. This is the hypothesis advanced by Knopf and Thelen⁹ who conclude that, "... it is apparent that the inclusions represent basic segregations from the granitic magma, and are characterized by high concentrations of the so-called usual accessories." Grout¹⁰ says that the dark spots are believed to "result from some obscure process of segregation or secretion." Likewise, Bastin¹¹ described in a porphyritic granite in Maine similar inclusions as "probably the result of combined flowage and basic segregation about many centers." Pabst,¹² in the use of the term "autolith" for the inclusions of the Sierra Nevada, implies that they are genetically related to the enclosing rock. Others, among them Grubenmann¹³ and Riegner,¹⁴ aside from stating that the inclusions are related to the enclosing rock, have avoided any further speculation regarding their origin.

Another explanation of the origin of inclusions that was formerly widely held is that of liquation. This idea was suggested by Backstrom,¹⁵ Weed and Pirsson,¹⁶ and Daly,¹⁷ but is no longer considered applicable and has lost favor even among its former proponents.

Still another mechanism by which inclusions of the nature of those under discussion could form is by introduction of foreign material and its partial or complete reaction with the magma. This was suggested by Gilbert¹⁸ in 1906 as the origin of dark inclusions

⁹ Knopf, A., and Thelen, P., Sketch of the Geology of Mineral King, California: *Univ. of California Pubs. Geol.*, vol. 4, 1905.

¹⁰ Grout, F. F., Probable Extent of Abyssal Assimilation: *Bull. Geol. Soc. Am.*, vol. 41, 1930.

¹¹ Bastin, E. S., The Geology of the Pegmatites and Associated Rocks of Maine: *U. S. Geol. Survey, Bull.* 445, 1911.

¹² Pabst, Adolf, Observations on Inclusions in the Granitic Rocks of the Sierra Nevada: *Univ. of California Pubs. Geol.*, vol. 47, pp. 325-386, 1928.

¹³ Grubenmann, U., Über der Tonalitkern des Ifinger bei Meran: *Vierteljahrsschrift d. Naturf. Gesell. Zurich*, vol. 41, 1896.

¹⁴ Milch u. Riegner, Über Basische Konkretionen und Verwandte Konstitution-facies im Granit von Striegau: *Neues Jahrb. Beilb.*, vol. 29, 1910.

¹⁵ Backstrom, H., Causes of Magmatic Differentiation: *Journal of Geology*, vol. 1, pp. 777-778, 1893.

¹⁶ Weed and Pirsson, Geology of the Castle Mountains Mining District, Montana: *U. S. Geol. Survey, Bull.* vol. 139, 1896.

¹⁷ Daly, R. A., Igneous Rocks and Their Origin, *New York*, 1914.

¹⁸ Gilbert, G. K., Gravitational Assemblage in Granite: *Bull. Geol. Soc. Am.*, vol. 17, 1906.

in Kings River County, California. More recently the same conclusion was reached by Nockolds¹⁹ in the granite of Bibette Head, Alderney. Likewise, Thomas and Smith²⁰ describe inclusions from the Tregastel Plounanach granite, Côtes du Nord, France, where adequate data are at hand to prove that the inclusions are xenoliths of older rock.

The only logical conclusion that can be drawn from the data and observations presented in the preceding pages is in accord with these last-named authors; namely, that the reaction inclusions of the Bonsall tonalite are xenoliths of older rock included in that body, and altered by reaction.

ORIGIN OF THE REACTION INCLUSIONS. The San Marcos Mountain gabbro is the only granular igneous rock of this province older than the Bonsall tonalite, and hence a likely source of material included in it. Further, microscopic analysis brings out the fact that mineralogically the inclusions resemble the gabbro in several respects. The best evidence is the identification in the inclusions of plagioclase feldspar containing about 90% of the anorthite molecule. This feldspar is an exceedingly uncommon mineral in igneous rock, and is entirely absent from the Bonsall tonalite. However, feldspar of identical composition is common in the older gabbro. Moreover, hypersthene and augite, common minerals of the gabbro are both present in the inclusions but absent from the tonalite. When these facts are considered, the evidence pointing to the gabbro as the source of the reaction inclusions of the tonalite is not only impressive but convincing.

ACTION OF TONALITE MAGMA ON GABBRO XENOLITHS. Even though there is adequate proof that the inclusions were contributed by the gabbro, the fact remains that in many ways they do not now resemble it. One can readily understand that with less evidence than is here at hand the inclusions might well be termed "autoliths," for they have so many features in common with the surrounding rock. In order for xenoliths of gabbro to lose their identity to such an extent, considerable reaction must have taken place between the original included rock and the magma. A comparison of the mineral composition of the gabbro and inclusions will serve to bring out the differences between the two and show the changes that have taken place.

¹⁹ Nockolds, S. R., The Contaminated Granite of Bibette Head, Alderney: *Geol. Mag.*, vol. 69, 1932.

²⁰ Thomas and Smith, Xenoliths of Igneous Origin in Tregastel Plounanach Granite Côtes du Nord, France: *Quart. Jour. Geol. Soc.*, vol. 88, part 2, 1932.

The mineral compositions below can be considered typical, although considerable variation may be found in both. From this comparison, it can be seen that the two major differences between the reaction inclusions and the gabbro are found in the composition of the feldspar and in the dark minerals. What would be the effect

MINERAL COMPARISON OF GABBRO AND INCLUSION

	Aver. Gabbro	Aver. React. Incl.
Plagioclase	65% An ₆₀	60% An ₄₅
Hypersthene	10	trace
Augite	10	trace
Hornblende	13	20
Quartz	locally	3
Biotite	locally	16
Magnetite	2	1

on small gabbro fragments immersed for a long time in the tonalite magma? Would the products of the resulting reaction be quantitatively, as well as qualitatively, sufficient to account for the present differences?

Let us consider the reactions that would take place, following Bowen, on immersing a gabbro inclusion in a magma of the composition of the tonalite. To quote Bowen,²¹ “. . . saturated granitic magma cannot dissolve inclusions of more basic rocks. The magma will, however, react with the inclusions and effect changes in them which give them a mineral constitution similar to that of the granite.” In the present case, therefore, we would not expect solution but rather a reaction which would render the gabbro minerals similar to those of the tonalite. The high calcic feldspar of the gabbro with An₇₅ would be out of equilibrium with the magma and would be made over into feldspar with more albite. Lime would be taken from the inclusions, and soda would be contributed by the magma. If sufficient time were available, the feldspar of the inclusion would eventually be made over so as to be identical with that of the host rock. However, zoning of the feldspar in both shows that cooling was too rapid to permit complete reaction. Equilibrium, therefore, was never attained, but the results approximate very closely what one would expect theoretically.

If reaction of the feldspar and magma took place according to the reaction principle, the net result would be a relative increase of lime over soda in the magma, and an increase of soda over lime in

²¹ Bowen, N. L., *The Evolution of the Igneous Rocks*, Princeton, 1928.

the inclusions. In the case of the dark minerals, the chemical interchange of material is not as simple. Nevertheless, the qualitative mineralogical changes are those one would expect. The dark mineral of the tonalite lowest in the reaction series is biotite. Therefore, according to Bowen, the magma was saturated with biotite and was also effectively saturated with olivine, pyroxene and hornblende, and could not dissolve them in spite of the marked contrast in composition. "But," to quote Bowen, "the magma can and will react with these minerals to convert them into biotite, usually by steps." This is apparently what has taken place in the gabbro xenoliths. The small amounts of olivine that are present in the gabbro would be the first minerals to react with the magma forming pyroxene. This, together with the original pyroxene, would then react to form hornblende. On continued cooling the hornblende thus formed would be converted to biotite with the introduction of the necessary potash. The process would go on until all the dark minerals were made over to biotite; or, due to subtraction of material necessary to produce biotite, the precipitation of minerals with which the magma is saturated brings reaction to an end. Following Bowen, the latter is apparently what happened, for the process was stopped before a large percentage of the hornblende was converted to biotite. However, it may have been that both hornblende and biotite were in equilibrium toward the end, and were crystallizing at the same time. This relation is shown in the tonalite where undoubtedly both minerals were at the same time in equilibrium with the magma, and hence it would be true for the inclusions.

Inasmuch as the gabbro is variable in composition and one cannot tell the percentages of hypersthene, augite, and hornblende of the original xenoliths, it is impossible to get for even one inclusion a quantitative estimate of the interchange of material. It was at first thought that a comparison of the chemical compositions of the gabbro and inclusions would aid in this respect; but, since both rocks have such a variable mineral composition, the comparison of individual analyses would have little significance.

In the comparison of the dark minerals of the tonalite with those of the inclusions, it was found that both the hornblende and biotite of the inclusions were richer in magnesia than the corresponding minerals of the host. This fact is additional evidence that equilibrium was not attained. From a chemical analysis of the gabbro

it was estimated that the ratio of $\text{MgO}:\text{FeO}$ as found in the ferromagnesian minerals is about 2.5:1, while from the analysis of the tonalite the same ratio is about 1:1. Although the ratios would vary slightly from place to place in both rocks, the comparison does give the order of magnitude. Diffusion, therefore, was apparently unable to take place fast enough to completely reduce the high ratio of $\text{MgO}:\text{FeO}$ in the gabbro to that of the tonalite. Where reaction was more complete, the composition of the corresponding minerals in host and inclusion is found to be the same. This conclusion is substantiated by the comparisons of the dark minerals of the tonalite and inclusions. In six out of eight cases where the hornblende of the inclusion was richer in magnesia than that of the tonalite, the biotite also had a higher MgO ratio. In all of these instances feldspar with anorthite cores was found in the inclusions. On the other hand, in the two comparisons in which the corresponding hornblende had similar composition, there were no anorthite cores in the feldspar. Reaction here had been complete.

NOTE ON THE STRUCTURE OF DICKITE AND OTHER CLAY MINERALS

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Diffraction data from x -ray powder photographs of several clay minerals taken by Gruner in combination with the results of a structure analysis of mica as published by Pauling have enabled Gruner to propose plausible structures for kaolinite, dickite, nacrite, vermiculite, talc, and pyrophyllite. However, as is well known, diffraction data from powder photographs are, generally speaking, insufficient for establishing uniquely the crystal structure of monoclinic minerals with many parameters. Until verified by further experimental evidence the structures assigned to these minerals should therefore be regarded as tentative.

On account of the physical properties of the material, it is of course very difficult to obtain single crystal measurements from any of the clay minerals, which is the obvious reason why Gruner used only powder photographs in his investigation. Dickite, however, often seems to grow in somewhat better crystals than any of its congeners, and in a sample of dickite from Pine Knot Colliery, Schuylkill Co., Pa.,¹ we have been able to find individual crystals large enough for a röntgenographic study. A small crystal, 0.4 mm. long, 0.04 mm. broad, and 0.02 mm. thick was mounted on a Weissenberg goniometer,² and x -ray photographs were taken with the crystal rotating about the a -axis and also about the b -axis. A Laue photograph normal to the base was also taken. The present paper is concerned with the experimental data thus obtained, and with the agreement between these data and the structure proposed for dickite by Gruner.

OPTICAL PROPERTIES

The plane of the optical axes is normal to the plane of symmetry and inclined 16° , rear to the normal to (001); $b=\gamma$; $a:\beta=16^\circ$;

¹ Beautiful samples of transparent but minute crystals of dickite (labeled Honess & Williams) were kindly sent to us by Dr. F. J. Williams, Pennsylvania State College, to whom we are indebted.

² We have used much smaller crystals than that of dickite in our x -ray work. They require a somewhat longer exposure, but the resulting photographs are uniformly more satisfactory than those from large-size crystals (see Fig. 1). Manipulation of such small crystals, however, requires a slightly modified technique compared with that of optical goniometry: the adjustment and orientation can be effected only photographically and with x -rays.

optically positive with $2V=70^\circ$; no perceptible dispersion. (These measurements were made with a Fedorov stage and are accurate to 2° .) The indices of refraction are: $\alpha=1.562$, $\beta=1.565$, $\gamma=1.571$, all probably within ± 0.001 (Na-light). These properties identify the mineral as dickite.³

UNIT CELL DIMENSIONS

The geometrical elements of dickite, as derived from our x -ray measurements are given in Table 1. With them are compared the elements derived from measurements with the reflection goniometer by Miers,⁴ and the planar spacings of Gruner,⁵ who, however, had to use Miers' value of the angle β in order to arrive at the spacings.

TABLE 1
GEOMETRICAL ELEMENTS OF DICKITE

a_0	b_0	c_0	a	b	c		
5.145	8.882	14.337	0.5789	: 1 :	1.6142	$96^\circ 45'$	Ksanda and Barth
—	—	—	0.5748	: 1 :	1.5997	$96^\circ 49'$	Miers
5.14	8.94	14.42	—	—	—	—	Gruner

The accuracy of the spacings can be seen from Tables 2 to 5 in which the new x -ray measurements have been listed. The angle β has been determined with an accuracy of $\pm 10'$. Our values lead to a unit cell containing four molecules of the formula $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$; calculated density: $\rho \text{ calc.} = 2.618$, density measured by immersion: $\rho = 2.62$.⁶

ATOMIC ARRANGEMENT

The correct space group of dickite, as indicated by the usual x -ray criteria, is either C_{2h}^6 or C_s^4 . The difference between them is that C_{2h}^6 has a symmetry center which is lacking in C_s^4 . A test for piezo-electricity⁷ gave a negative result, which makes C_s^4 improb-

³ Ross, C. S., and Kerr, P. F., The kaolin minerals: *U. S. Geol. Surv.*, Prof. Paper 165 E, pp. 151-180, 1931.

⁴ Miers, H. A., *Mineral. Mag.*, vol. 9, p. 4, 1890.

⁵ Gruner, J. W., The crystal structure of dickite: *Z. Krist.*, vol. 83, pp. 394-404, 1932.

⁶ Dick, Allan B., On kaolinite: *Mineral Mag.*, vol. 8, pp. 15-27, 1888.

⁷ Kindly made by Dr. R. T. Milner of the U. S. Bureau of Chemistry and Soils on two samples of dickite, one from Pine Knot Colliery, Schuylkill Co., Pa., and the other from Red Mountain, Colo.

able. In his paper on dickite Gruner⁸ has considered two different structural arrangements which he has called arrangement A and arrangement B, both isomorphous with C_s^4 . For both arrangements he has calculated the product $j \cdot F^2$ (the frequency factor times the structure factor) for all reflections down to a spacing of 1.300 using for them the F -values given in Wyckoff's tables.⁹ By multiplying



FIG. 1. Equatorial Weissenberg photograph of dickite rotated about the a -axis and taken with copper radiation.

this product by the function of the glancing angle and correcting for the difference in j , we should thus, if either of the two arrangements were correct, obtain figures which would be proportional to the observed intensities.

An inspection of the tables 2 to 8 shows that the agreement between calculated and observed intensities is not satisfactory;¹⁰

⁸ *Op. cit.*

⁹ Wyckoff, R. W. G., *The Structure of Crystals*, 2d ed., 1931, pp. 95 and 100.

¹⁰ The intensity data listed in Tables 2, 3, 4, and 6, 7, 8 are all based on Weissenberg photographs of one and the same crystal of dickite. Except in Table 6, 10 indicates the strongest and 1 the weakest intensity of any visible spot. The intensities obtained with Cu-radiation are not directly comparable with those obtained with Mo-radiation.

but certain sets of reflections are in better agreement with the calculations than others. In particular it is noticed that the reflections from the base and from the front pinacoid are in fair agreement with the calculations, whereas the reflections from the side pinacoid are very much off (see Tables 4, 5, and 2 respectively). A trial calculation also showed that a slight readjustment of some of the 13 parameter values along the *c*-direction would produce a still better fit between the observed and calculated intensities of the basal reflections.

The new *x*-ray data thus permit of the following conclusions:

(1) The shape and dimensions of the unit cell of dickite have been correctly determined by Gruner.

(2) Dickite is composed of discrete sheets of cations and anions parallel to the *a*-*b* plane stacked on top of each other in the manner described by Gruner.

(3) The two-dimensional arrangement of the several atoms within each sheet is, however, different from any of the arrangements considered by Gruner.

(4) Since the crystal structures of kaolinite,¹¹ nacrite,¹² vermiculite,¹³ and halloysite¹⁴ have been calculated on the basis of the incorrect structure of dickite, the proposed structures of all these minerals cannot be accepted as being correct without further proof.

TABLE 2
REFLECTIONS FROM THE SIDE PINACOID (EQUATORIAL PHOTOGRAPH OF A
SINGLE CRYSTAL OF DICKITE, ROTATED ABOUT THE *a*-AXIS)

Indices	<i>CuK</i> radiation	<i>d</i>	<i>d</i> ₀₁₀	Intensity		
				Calculated for position		Observed
				<i>A</i>	<i>B</i>	
020	β	4.431	8.862			
020	$\alpha_1 + \alpha_2$	4.430	8.860	0.0	4.7	4
040	$\alpha_1 + \alpha_2$	2.220	8.880	0.8	0.0	1+
060	β	1.478	8.868			
060	$\alpha_1 + \alpha_2$	1.477	8.862	6.6	6.6	4+
$b_0 = d_{010} = 8.867 \text{ \AA}$						

¹¹ Gruner, J. W., *Z. Krist.*, vol. **83**, pp. 75-88, 1932.

¹² *Z. Krist.*, vol. **85**, pp. 345-354, 1933.

¹³ *Am. Mineral.*, vol. **19**, pp. 557-575, 1934.

¹⁴ Mehmel, M., Über die Struktur von Halloysit und Metahalloysit: *Z. Krist.*, vol. **90**, pp. 35-43, 1935.

TABLE 3
REFLECTIONS FROM THE FRONT PINACOID (EQUATORIAL PHOTOGRAPH OF
A SINGLE CRYSTAL OF DICKITE ROTATED ABOUT THE *b*-AXIS)

Indices	<i>MoK</i> radiation	<i>d</i>	<i>d</i> ₁₀₀	Intensity	
				Calculated	Observed
200	$\alpha_1 + \alpha_2$	2.555	5.110	5.0	5
400	$\alpha_1 + \alpha_2$	1.278	5.112	3.0	2
600	$\alpha_1 + \alpha_2$			0.3	0

$d_{100} = 5.111 \text{ \AA}$
 $a_0 = 5.146 \text{ \AA}$

TABLE 4
REFLECTIONS FROM THE BASE

CuK α and CuK β radiation						MoK α radiation	
Indices	Radiation	d	d_{001}	Intensity		d	d_{001}
				Calc.*	Obs.		
002	β	7.119	14.238				
002	$\alpha_1 + \alpha_2$	7.120	14.240	17.8	9	7.118	14.236
004	β	3.555	14.220				
004	$\alpha_1 + \alpha_2$	3.556	14.224	21.8	10	3.551	14.204
006	β	2.372	14.232				
006	$\alpha_1 + \alpha_2$	2.371	14.226	6.0	8	2.376	14.256
008	β	1.780	14.240				
008	$\alpha_1 + \alpha_2$	1.779	14.232	1.3	8	1.781	14.248
0010	β	1.422	14.220				
0010	α_1	1.422	14.220	2.0	5	1.423	14.230
0010	α_2	1.423	14.230				
0012	β	1.186	14.232				
0012	α_1	1.186	14.232	1.7	6	1.189	14.268
0012	α_2	1.186	14.232				
0014	β	1.017	14.238				
0014	α_1	1.016	14.224	0.6	3	1.019	14.266
0014	α_2	1.016	14.224				
0016	β	.890	14.240				
0016	α_1	.890	14.240	1.4	6	.890	14.240
0016	α_2	.890	14.240				
0018	α_1	.7915	14.247	0.7	2		
0018	α_2	.7918	14.252				
0020	β	.7126	14.252	.2	1		

$d_{001} = 14.233 \text{ \AA}$
 $c_0 = 14.332 \text{ \AA}$

$d_{001} = 14.243 \text{ \AA}$
 $c_0 = 14.342 \text{ \AA}$

* The calculated intensities of Gruner in this case have been checked by the use of Bragg's *F*-values and the theoretical chemical formula for dickite. This affects the intensities in the decimal place only; some intensities of low spacings have not been calculated by Gruner, for them also Bragg's *F*-values have been used.

TABLE 5
MEASUREMENTS FROM ROTATION PHOTOGRAPHS OF A
SINGLE CRYSTAL OF DICKITE

The crystal of dickite rotated about <i>a</i> -axis, <i>CuK</i> radiation			The crystal of dickite rotated about <i>b</i> -axis, <i>MoK</i> radiation		
Layer-line	a_0/n	a_0	Layer-line	b_0/n	b_0
1	5.175	5.175	1	8.915	8.915
2	2.565	5.130	2	4.444	8.888
3	1.710	5.130	3	2.972	8.916
		$a_0 = 5.145 \text{ \AA}$	4	2.222	8.888
			5	1.782	8.910
			6	1.478	8.868
					$b_0 = 8.898 \text{ \AA}$

TABLE 6
INTENSITY DATA FROM AN EQUATORIAL PHOTOGRAPH OF A SINGLE CRYSTAL
OF DICKITE, ROTATED ABOUT THE *a*-AXIS, *CuK* RADIATION

Indices	Calculated for position		Observed
	A	B	
021	4.8	4.8	7
022	4.6	0.4	8
023	2.0	4.6	3+
024	0.7	0.7	6
025	0.6	0.5	2
026	0.4	0.3	3
027	0.2	0.7	0
028	0.4	0.0	3-
029	0.1	0.2	1
041	0.2	0.4	1
042	0.2	0.4	2
043	0.4	0.8	2-
044	0.8	0.0	5
045	0.5	0.6	3+
046	0.0	0.4	1
047	0.5	0.4	3+
048	0.5	0.1	4
061	0.0	0.0	0
062	1.3	1.3	1+
063	0.0	0.0	0
064	0.5	0.5	1

TABLE 7

INTENSITY DATA FROM AN EQUATORIAL PHOTOGRAPH OF A SINGLE CRYSTAL
OF DICKITE ROTATED ABOUT THE *b*-AXIS, *MoK* RADIATION

Indices	Calculated	Observed
20 $\bar{2}$	7.4	6
202	23.3	10
20 $\bar{4}$	0.7	3
204	7.4	6
20 $\bar{6}$	2.6	4
206	9.6	7
20 $\bar{8}$	4.9	3
208	1.5	2

TABLE 8

INTENSITY DATA FROM THE THIRD LAYER-LINE PHOTOGRAPH OF A SINGLE
CRYSTAL OF DICKITE ROTATED ABOUT THE *b*-AXIS, *MoK* RADIATION.

DENOTATION OF SYMBOLS: *s* = STRONG; *m* = MEDIUM; *w* = WEAK

Indices	Calculated	Observed
130	0.0	0
13 $\bar{1}$	4.3	<i>m</i> —
131	7.6	<i>s</i>
13 $\bar{2}$	0.0	0
132	0.0	0
13 $\bar{3}$	9.5	<i>s</i> —
133	1.0	<i>m</i>
13 $\bar{4}$	0.0	0
134	0.0	0
13 $\bar{5}$	5.8	<i>m</i>
135	2.2	<i>m</i>
13 $\bar{6}$	0.0	0
136	0.0	0
13 $\bar{7}$	9.8	<i>m</i>
137	5.0	<i>m</i>
13 $\bar{8}$	0.0	0
138	0.0	0
13 $\bar{9}$	1.5	<i>w</i>
139	10.2	<i>m</i> —
330	0.0	0
33 $\bar{1}$	11.0	<i>s</i>
331	2.5	<i>s</i> —
33 $\bar{2}$	0.0	0
332	0.0	0
33 $\bar{3}$	2.2	<i>m</i>
333	0.9	<i>w</i>
33 $\bar{4}$	0.0	0
335	1.7	<i>m</i>
33 $\bar{6}$	0.0	0

PARAGENESIS OF THE MINERAL ASSEMBLAGE AT CRESTMORE, RIVERSIDE COUNTY, CALIFORNIA

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INTRODUCTION

For more than twenty years the Crestmore locality has excited the interest of mineralogists. This interest was first aroused when specimens of blue calcite with monticellite and xanthophyllite were sent to A. S. Eakle. The first publication appeared in 1914¹ and since then numerous papers have been published on the mineralogy of Crestmore by A. S. Eakle, W. F. Foshag, A. F. Rogers, and others.

Crestmore is situated on the extreme eastern lobe of the Jurupa Mountains about three miles west of Riverside, California. The Jurupa Mountains are an east-west range roughly eight miles long and three miles wide which parallels the front of the San Gabriel Mountains.

The cement plant, limestone quarries, and mine of the Riverside Cement Company are located at Crestmore. Quarrying operations were started some seventeen years ago. The rocks were at first used as road metal, burned lime for sugar refining, and for the manufacture of cement. With the increased demand for cement the quarrying operations were given over entirely to that purpose. At the present time the material is obtained by underground mining.

PURPOSE AND METHOD OF INVESTIGATION

Although much work has been done on the mineralogy of the limestones and associated rocks at Crestmore, never before has the geology been mapped and the mineralogy studied in its relation to the geology of the district for the purpose of determining the paragenesis of the minerals and their petrological associations. With this purpose in mind as a major objective, the work was conducted and resulted in the following related units:

1. Detailed geologic study of the Crestmore quarries and the eastern portion of the Jurupa Mountains.

¹ Eakle, A. S., and Rogers, A. F., Wilkeite, A New Mineral of the Apatite Group and Okenite, Its Alteration Product: *Am. Jour. Sci.*, vol. 27, pp. 262-267, 1914.

2. Economic study of a typical Southern California limestone deposit.

3. Collection and determination of a large amount of mineralogical material by chemical analysis and optical methods.

4. Organization of this material into a catalogue of mineralogical associations.

Unfortunately some of the rare minerals described from this locality were entirely removed during the quarrying operations. Hence in preparing a catalogue of the mineral species it was necessary to take some of the data from the literature and in these cases the relationships and associations could not be precisely determined.

The map of the Crestmore quarries was made on the scale of $1'' = 100'$ on a topographic map kindly furnished by the Riverside Cement Company. The hills to the west of the quarries were mapped on a portion of the U.S.G.S. San Bernardino Quadrangle, originally on the scale of $1'' = 1$ mile photographically enlarged to 1 inch equals one-half mile. Locations were determined by means of a Brunton compass and a light plane table.

ACKNOWLEDGMENTS

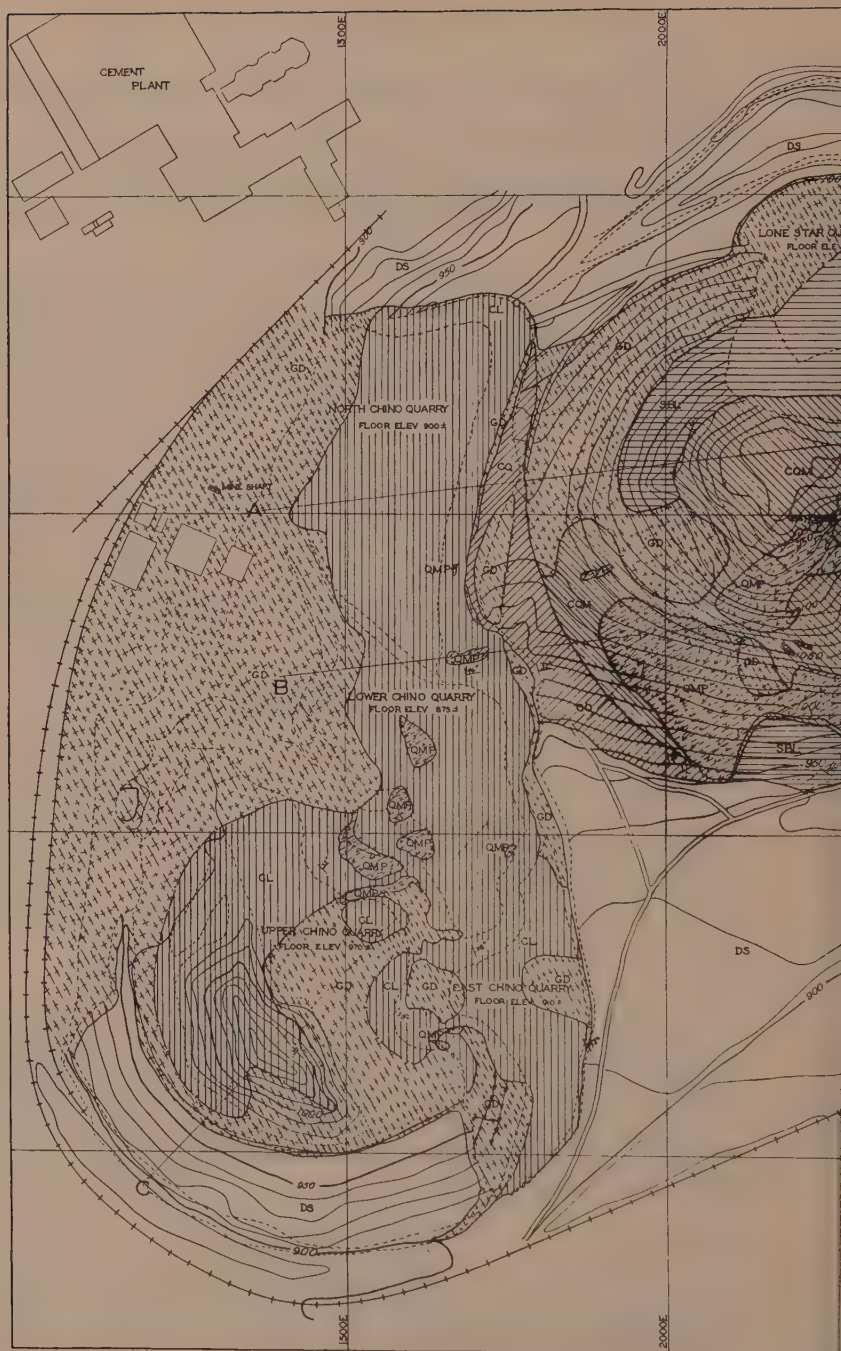
The writer wishes to thank the officials of the Riverside Cement Company, Mr. John Treanor, Mr. G. A. Beckett, and Mr. Earl MacDonald, for their permission to make a geologic map of the quarries. Messrs. Thomas Mullan and C. A. Robotham of the same organization were very helpful. Much credit is due Dr. René Engel, of the California Institute of Technology, under whose direction this work was conducted, for the help he has given.

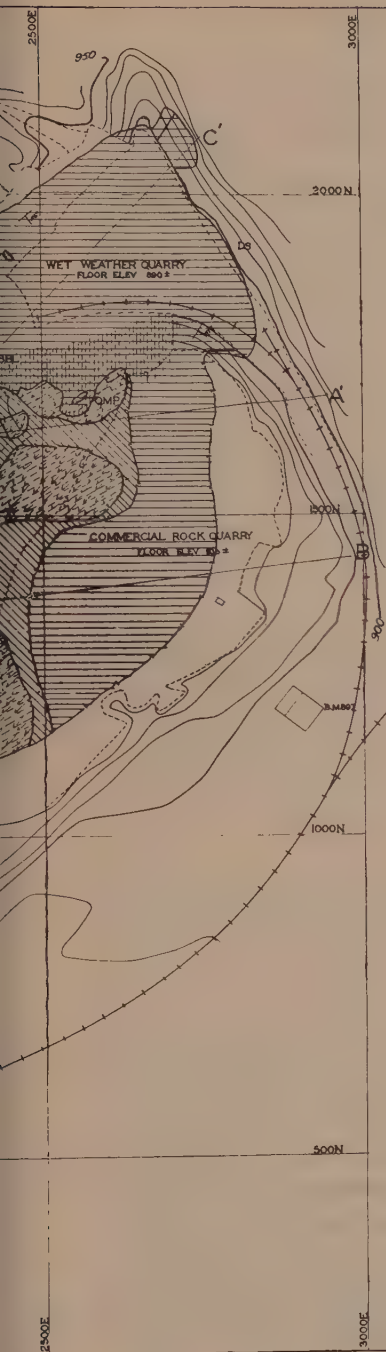
GEOLOGY

The geologic study of the district and the economic aspects of the Crestmore limestones will be the subject of another paper. However, it is entirely within the scope of the present paper and will add materially to its value to give here a brief resumé of the geology. A geologic and topographic map of the Crestmore quarries is shown on Plate 1.

Stratigraphy.

The oldest rocks of the Jurupa Mountains form a thick series of recrystallized sedimentaries for which the name, Jurupa Series, is proposed. The stratigraphically lower part of the section, consist-





GEOLOGIC MAP OF THE **CRESTMORE QUARRIES** RIVERSIDE CO., CALIF.

EXPLANATION

QUATERNARY ALLUVIUM

QAS
DUNE SANDS

INTRUSIVE ROCKS
PRE-CRETACEOUS

PEGMATITE DIKES
QMP

QTZ. MONZONITE PORPHYRY

GRANODIORITE

METAMORPHIC ROCKS
JURUPA SERIES - PALEOZOIC?

WHITE CALCITE BLUE CALCITE
SKY BLUE QUARRY LIMESTONE

CHINO QUARRY QUARTZITE

CHINO QUARRY LIMESTONE

CONTACT ROCK

ASSOCIATED WITH Q. MONZONITE P.

SYMBOLS

CONTACT: CERTAIN — DOUBTFUL, ---
FAULT ———
DIP AND STRIKE ———
QUARRY BOUNDARY - - - - -
ADIT ———
RAILROAD ———

TOPOGRAPHY BY RIVERSIDE CEMENT COMPANY
GEOLOGY BY JOHN W. DALY JUNE 1930

100 0 100 200 300
SCALE IN FEET
CONTOUR INTERVAL 10'



ing of undifferentiated quartzites, schists and gneisses with small limestone lenses, will be referred to as the Undifferentiated Complex. Lying on this complex, with the same attitude and possibly conformably, are the limestones which are exploited for cement manufacture. These were differentiated on the large scale map of the Crestmore quarries (Plate 1) into the following units: (1) The lower, Chino Quarry limestone, (2) Overlying quartzite and schist beds, called the Chino Quarry quartzite, (3) The upper, or Sky Blue Quarry limestone. Granodiorite and quartz monzonite intrusions separate these lower members from the upper limestone. In mapping this last unit an effort was made to trace the limits of the development of the blue calcite. Because of the uncertain nature of the outcrops this distribution could not be carried through in detail but is indicated in a general way on the map (Plate 1).

The Undifferentiated Complex.

These rocks are best exposed in the hills about two miles northwest of Crestmore. The stratigraphic units are tabulated below in descending order:

1700 ft. thin bedded quartzite interstratified with fissile mica schist.

850 ft. coarse bedded quartzitic schists.

1050 ft. biotite gneiss in part schistose.

100 ft. hard, thick bedded, quartzite in part schistose.

3700 ft. +

Granodiorite cuts off the base of the section and intrudes parts of it thus making it impossible to determine the true thickness of the section.

The Chino Quarry Limestone.

This limestone, the best exposure of which is in the Chino quarry, is white, medium to thin bedded, and medium to coarsely granular. Graphitic beds are found throughout the section but are more common near the base. Another conspicuous rock type is the calcite-brucite rock, or predazzite. Pseudo-isometric crystals of brucite occur in beds of medium grained, white limestone. Rogers²

² Rogers, A. F., An American Occurrence of Periclase and its Bearing on the Origin and History of Calcite-Brucite Rocks: *Am. Jour. Sci.*, vol. 46, pp. 582-586, 1918. Periclase from Crestmore near Riverside, California, with a List of Minerals from this Locality: *Am. Mineral.*, vol. 14, pp. 462-469, 1929.

has shown that these brucite crystals are pseudomorphs after periclase, remnants of which can still be found enclosed in the brucite. Associated minerals are chondrodite, spinel, magnetite and wilkeite.

The base of this limestone has been cut off by granodiorite so that the true section cannot be ascertained. The maximum exposed thickness is of the order of 470 feet. The total would undoubtedly be considerably greater.

The Chino Quarry Quartzite.

The structural relations between the Chino Quarry quartzite and the Chino Quarry limestone is not precise. They are in part separated by a sill-like intrusion of granodiorite. Where their contact is exposed they are apparently conformable, but the quartzite has a shallower dip than the underlying limestone. The top of the quartzite has been cut off by intrusions of granodiorite and quartz monzonite porphyry, except at the eastern end where it appears to be unconformably overlain by limestone, but the exposures are poor and this relation is not certain. The examination of diamond drill cores and the underground workings proves that the downward extension of these rocks is severed by intrusions about two hundred feet below the surface.

A total thickness of at least 75 feet is exposed. The formation consists of interstratified, thin bedded, quartzite and fissile mica schists.

The Sky Blue Quarry Limestone.

Except for the development of the blue calcite and the more intense metamorphism near some of the quartz monzonite dikes, this formation is lithologically similar to the Chino Quarry limestone. There is no evidence to show that the original sediments of these two units differed appreciably in chemical composition. This study has proven that any differences are directly related to the varying degrees of metamorphism to which each limestone has been subjected.

Igneous intrusions have separated the Sky Blue Quarry limestone from the underlying Chino Quarry quartzite so that their relations can only be inferred. The attitude of the formations differs appreciably. This may be due to distortion during intrusion, or possibly the intrusion followed a line of previous structural weakness, i.e., an unconformity or a fault.

Alluvium covers the top of the section but a thickness of over 500 feet is exposed in the quarries.

Other Outcrops.

In the Jensen quarry to the west and in several other parts of the area studied, outcrops of limestone are found. They are lithologically similar to the limestones described above but their structural relations are so obscure that their further discussion in this paper is not warranted.

Age and Suggested Correlation of the Jurupa Series.

Because of the isolated position of this range and the lack of fossils, correlation had to be based on lithologic similarity. On this basis, the Undifferentiated Complex is thought to be the equivalent of the Arrastre quartzite and the limestones equivalent to the Furnace limestone described by Vaughan³ from the San Bernardino Mountains. Vaughan considered the Arrastre quartzite as lower Cambrian and the Furnace limestone as upper Cambrian and Ordovician. Later work by Woodford and Harriss⁴ proves that at least the upper portion of the Furnace limestone is Mississippian (?). Since it is apparent that the age of similar rocks is not precisely known, the Jurupa Series has been assigned to the Paleozoic (?) era without attempting to relate it to any particular period or periods.

Quaternary Alluvium.

Undifferentiated dune sands, river sands, and fan deposits are grouped under this unit.

IGNEOUS ROCKS

In this region five distinct but related plutonic rock types are found. Apparently these types are the result of differentiation from a parent magma and range from hypersthene quartz diorite to pegmatites.

Hypersthene Quartz Diorite.

This oldest and most basic rock outcrops on the hills southwest

³ Vaughan, F. E., *Geology of the San Bernardino Mountains North of San Geronio Pass: Bull. Dept. Geol., Univ. Calif.*, vol. 13, pp. 319-412, 1922.

⁴ Woodford, A. O., and Harriss, R. S., *Geology of Blackhawk Canyon, San Bernardino Mountains, California: Bull. Dept. Geol., Univ. Calif.*, vol. 17, pp. 265-304, 1928.

of Crestmore. A microscopic determination shows the following: The texture is holocrystalline, medium grained, hypidiomorphic, inequigranular. The femic minerals are represented by slightly pleochroic hypersthene, hornblende, in part uraltic, and biotite. The feldspar is a basic andesine and shows slight zoning. Undulatory quartz was the last mineral to crystallize. Pyrite and apatite are the accessories. Near the periphery the rock shows textural and mineralogical differences. The texture is porphyritic. The phenocrysts are labradorite and the feldspar of the ground mass is andesine. Quartz is less abundant. These variations can be readily explained by the different rates of cooling that would obtain at the center and at the periphery of the mass.

Granodiorite.

It forms the bulk of the intrusive rocks in the area mapped. One of its most characteristic features is the presence of basic inclusions. These are roughly egg shaped, from two inches to one foot long, and are, to some extent, oriented with their long axes parallel to each other. The texture and the mineralogical constituents of these inclusions show their affinity with the peripheral phase of the hypersthene quartz diorite from which they were probably torn by the intruding granodiorite.

A holocrystalline, coarse to medium grained, hypidiomorphic, inequigranular texture is characteristic of the granodiorite. Most of the femic material is pleochroic hornblende. Chloritized biotite is present in lesser amounts. Sericitized oligoclase with subordinate amounts of orthoclase constitute the feldspathic elements. The abundant quartz shows undulatory extinction. The accessories are apatite, zircon and hematite.

Quartz Monzonite Porphyry.

Numerous intrusions of this rock cut the limestones in the Crestmore quarries and it is to solutions emanating from these intrusions that most of the rare minerals owe their genesis. The texture is holocrystalline porphyritic, hypidiomorphic, fine-grained, inequigranular. The feldspars are orthoclase and oligoclase both as phenocrysts and as constituents of the ground mass. They show alteration to calcite and sericite. Abundant quartz occurs in part in micropegmatitic intergrowth with the orthoclase. Scattered grains and aggregates of pale green augite constitute the femic

material. Pleochroic grains and aggregates of titanite are common. Apatite and pyrite are the accessories.

The peripheries of the larger dikes and of many of the smaller ones exhibit marked endomorphic effects resulting from the assimilation of foreign material and from more rapid cooling. In a general way these effects are:

(1) Frequent development of porphyritic texture.

(2) An increase in the abundance of the ferromagnesium constituents and a change in their character. In this case we have diopside, diallage, augite, and grossularite.

(3) An increase in the amount and basicity of the plagioclase.

(4) In many cases a complete disappearance of quartz.

Granite Porphyry.

The granite porphyry outcrop, in the western portion of the Jurupa Mountains, is too far removed from the quarries to merit close consideration in this paper, but its occurrence is interesting in its relation to the igneous sequence.

The texture is holocrystalline, medium grained, porphyritic, hypidiomorphic, inequigranular. Microcline, oligoclase, orthoclase, quartz, biotite, rutile, magnetite and apatite are the minerals represented.

Pegmatite Dikes.

In the literature on the Crestmore quarries the statement that the pegmatite dikes are abundant and commonly traverse the limestone is often made. The writer's observations are at variance with this statement for very few of these dikes are seen and never in the limestone. It is possible, however, that the dikes mentioned in the literature were small and were removed during quarrying operations.

An abundance of pegmatite dikes occurs in the hills adjacent to the quarries. They vary in width from less than an inch to as much as twenty-five feet and some of them can be traced for miles. Many of these dikes show banding. The outer bands are made up of layers, one-half to one inch thick, composed of graphic intergrowths of quartz and albite. The inner zone, having a width of about one-tenth the total thickness of the dike, is composed of extremely coarse feldspar and quartz with the occasional development of black tourmaline and biotite. The composition of the feldspar varies between albite and microcline.

Age and Sequence of the Intrusive Rocks.

Intrusions of Jurassic age occur in the Santa Ana Mountains and in the Julian district. Vaughan⁵ correlates the Cactus granite of the San Bernardino Mountains with the Jurassic granites of the Sierra Nevada but mentions an earlier intrusion which may belong to the Paleozoic. Since there is a possibility that the Jurupa Mountain intrusives might be earlier than Jurassic their age is designated merely as pre-Cretaceous.

The sequence of intrusions has followed the order: hypersthene quartz diorite, granodiorite, quartz monzonite porphyry, granite porphyry and pegmatite dikes. Their order and spatial relationship suggest differentiation from the same parent magma and that the intrusions followed closely in point of time.

CONTACT ROCKS

Three distinct types of contact rock have been formed by the quartz monzonite porphyry intrusions. These are listed below in the order of their importance.

Garnet Contact Rock.

The face of the Commercial Rock quarry and the crest of Sky Blue Hill is made up almost entirely of this material. The greatest proportion of the rock is badly fractured massive grossularite. Other minerals, in the order of their importance, are diopside, diallage, calcite, wollastonite, augite and scapolite.

Vesuvianite Contact Rock.

At the corner of Lone Star, Wet Weather and Commercial Rock quarries a contact rock consisting chiefly of vesuvianite and calcite is developed. The proportions of these minerals vary greatly. In places the rock is nearly all vesuvianite, quite massive and glassy, at others the calcite and vesuvianite are approximately in equal amounts. The other extreme is found when the mass is almost all calcite with only a few grains of vesuvianite embedded in it. The calcite occurs as a soft, white mass of aggregates of extremely fine needles and some very small rhombohedrons. These forms probably represent rapid crystallization from a supersaturated solution. Diopside, garnet and wollastonite are the minerals commonly associated with this rock.

⁵ Vaughan, F. E., *Op. cit.*, 1922.

In several places in the Wet Weather quarry this assemblage is found definitely confined to certain beds, thus indicating that the initial character of the limestone strata may have been one of the governing factors in its origin. It is interesting to note that in this case the calcite is quite coarsely crystalline.

Quartz and Garnet Contact Rock.

This rock is composed wholly of granular, vitreous quartz, and grossularite crystals and grains. It is found close to a small quartz monzonite porphyry dike near the outcrop of the Chino Quarry quartzite in the saddle north of the Chino quarry. This association indicates its derivation from an impure lime bearing sandstone.

MINERALOGY

It is impossible in this paper to include a complete catalogue of the minerals. Hence, the following descriptions are limited to new occurrences or to controversial subjects to which the author has new data to add.

Following this section the minerals are alphabetically tabulated in a manner which shows their petrologic distribution, their relative abundance and, to a large extent, their associations. For more detailed information the reader is referred to the abundant literature on this locality.

Sulphides: Eakle⁶ states that the sulphides are associated with the pegmatite intrusives. The author has not found this to be the case. Where the association has been seen the sulphides are concentrated near the quartz monzonite porphyry. No sulphides are found as accessories in the pegmatites, but they are present as such in the quartz monzonite porphyry. In the author's opinion solutions from the quartz monzonite deposited the sulphide mineralization found in the quarries.

Monticellite: This mineral has been described by Eakle⁷ from the blue calcite and later by Tilley⁸ from the contact rock. Eakle suggested that the monticellite results from the metamorphism of the brucite limestone, while the diopside and vesuvianite were formed during the metamorphism of the pure beds. Thus he accounts for

⁶ Eakle, A. S., Minerals Associated with Crystalline Limestone at Crestmore, Riverside County, California: *Bull. Dept. Geol., Univ. Calif.*, vol. 10, pp. 327-360, 1917.

⁷ *Op. cit.*, 1917.

⁸ Tilley, C. E., On a Custerite-bearing Contact Rock from California: *Geol. Magazine*, pp. 371-372, 1928.

the scarcity of monticellite and xanthophyllite. In an earlier paper Eakle⁹ attributed the formation of these minerals to solution action accompanying the quartz monzonite porphyry intrusion. The writer's observations confirm the earlier statement by Eakle, for otherwise it would imply that the brucite limestone is limited in extent, while, on the contrary, it is quite common.

Diallage: Diallage is found in the endomorphic phases of the quartz monzonite porphyry, and in the garnetiferous contact rock.

Orthoclase: According to Eakle¹⁰ orthoclase forms the larger portion of the pegmatite dikes. In the samples examined by the author no orthoclase was found in the pegmatites, only albite and microcline. It does occur, however, in the granodiorite, the granite porphyry and the quartz monzonite porphyry.

Oligoclase: This is the plagioclase feldspar of the granodiorite and also occurs in the enclaves in the granodiorite. It is a constituent mineral of the quartz monzonite porphyry, the hypersthene quartz diorite, the granite porphyry and the Undifferentiated Complex.

Labradorite: This has been described by Eakle¹¹ as one of the constituents of the granodiorite, along with oligoclase. No evidence has been found for two generations of plagioclase. The plagioclase is entirely oligoclase. Labradorite occurs as phenocrysts in the hypersthene quartz diorite and in some of the basic enclaves in the granodiorite. A few grains were found in the Undifferentiated Complex and the Chino Quarry quartzite.

Bytownite-Anorthite: Crystals of plagioclase of the bytownite-anorthite type were found in a small cavity at the border of one of the small quartz monzonite porphyry dikes in the lower Chino quarry. They were associated with pyrite, chalcopyrite and bornite.

Scapolite: A grey white scapolite with violet streaks has been mentioned by Eakle. The material collected by the author is white and composed of small radiating aggregates of extremely fine needles, so fine that to the unaided eye the material appears almost massive. It occurs in the contact rock associated with wollastonite, calcite, diopside, and grossularite, surrounding these minerals and filling spaces between them. The indices, $\omega = 1.567 \pm .005$, $\epsilon = 1.548$

⁹ Eakle, A. S., Xanthophyllite in Crystalline Limestone: *Jour. Wash. Acad. Sci.*, vol. 6, pp. 332-335, 1916.

¹⁰ *Op. cit.*, 1917.

¹¹ *Op. cit.*, 1917.

$\pm .005$, measured on one sample would indicate, according to Winchell's¹² diagram marialite 60%, meionite 40%, or the species dipyrrite. Another sample gave values $\omega = 1.504 \pm .005$, $\epsilon = 1.550 \pm .005$, which corresponds to the values of a mixture of 40% marialite, and 60% meionite, or the species mizzonite. This is an uncommon form of crystallization for scapolite. The fine crystallinity would suggest extremely rapid growth of crystals by rapid cooling of a supersaturated solution. However, the associated minerals are very coarse, so that this condition does not apply to all of them.

Clinozoisite: A pale, transparent to translucent, greenish grey variety occurs in shattered crystals and grains in a small contact mass associated with one of the smaller quartz monzonite porphyry dikes in the Chino quarry. The associated minerals are garnet and calcite. This undoubtedly results from the hydrothermal action of solutions from the quartz monzonite porphyry on the limestone.

Epidote: Small black crystals, up to three millimeters in length, were found disseminated in the white Chino limestone and associated with the deweylite and chrysotile, near a dike of quartz monzonite porphyry. A green epidote is abundant in some of the pegmatites as already noted by Eakle.

Xanthophyllite: This mineral was first described from this locality by Eakle¹³ as disseminated in the blue calcite and associated with monticellite. The above occurrence was not found but small crystals and flakes were found in a locally developed, coarsely crystalline green calcite in the Chino Quarry limestone that was associated with a small dike of quartz monzonite porphyry.

Chrysotile and Deweylite: A massive green mineral was found in the white calcite of the Chino Quarry limestone in East Chino quarry, a few feet from a small quartz monzonite dike. An analysis was made by Mr. Thomas Mullan of the Riverside Cement Company and the following results were obtained:

SiO ₂	40.88
(Fe, Al) ₂ O ₃	1.27
CaO	5.91
MgO	37.52
H ₂ O	12.00
CO ₂	2.50
	<hr/> 100.08

¹² Winchell, A. N., The Properties of Scapolite.: *Am. Mineral.*, vol. 9, pp. 108-112, 1924.

¹³ *Op. cit.*, 1917.

Calcite grains could be seen in the material so CaCO_3 and $(\text{Fe, Al})_2\text{O}_3$ were discarded and the other figures recalculated on the basis of 100 per cent.

	per cent	mol-numbers	ratios
SiO_2	45.20 .....	.75	3
MgO	41.50	1.04	4
H_2O	13.30 .....	.74	3

This gives the formula $3\text{H}_2\text{O} \cdot 4\text{MgO} \cdot 3\text{SiO}_2$, or $\text{H}_6\text{Mg}_4\text{Si}_3\text{O}_{13}$, which does not correspond with any of the known hydrous magnesium-silicate minerals. Grains of the material show indices as follows: A minimum of $1.528 \pm .005$, the maximum is $1.555 \pm .005$. If this were one mineral the birefringence would be 0.027, which is much too great in comparison with the observed birefringence. Thus it is thought that this represents a mixture of chrysotile and deweylite. A mixture of these minerals in the proportion 68.8% deweylite and 31.2% chrysotile would give an analysis corresponding to the above one. A thin section of the material proved that two minerals were present.

Rogers¹⁴ describes deweylite replacing hydromagnesite in the calcite-brucite rock, and regards it as a supergene mineral. In view of its present relation to the quartz monzonite porphyry dike it seems that the genesis of these silicates can be assigned to the action of solutions emanating from this dike on previously formed minerals (epidote or diopside as suggested by their nearby occurrence) and thus in this case their origin would be hypogene.

Sepiolite: A white, fibrous mineral was found filling small veins in the calcite near the occurrence of the chrysotile and deweylite. The material is composed of finely interlocked fibers with the fibers oriented parallel to the vein walls. An analysis by Mr. Mullan gave the following results:

SiO_2	44.38
$(\text{Fe, Al})_2\text{O}_3$	0.82
CaO	11.90
MgO	20.24
H_2O	13.09
CO_2	9.49
Total.....	99.92

The nature of the material made it impossible to free it, for analysis, from small grains of calcite so that CaCO_3 and $(\text{Fe, Al})_2\text{O}_3$ were removed and the figures recalculated to 100 per cent.

¹⁴ *Op. cit.*, 1918.

	per cent	mol-number	ratios
SiO ₂	57.00 .....	.95	3
MgO	26.00 .....	.645	2
H ₂ O	17.00 .....	.945	3

The above ratios correspond to the formula: $2\text{MgO} \cdot 3\text{SiO}_2 \cdot 3\text{H}_2\text{O}$. This probably represents a mineral between sepiolite and parasepiolite, but since the water content of sepiolite is variable the mineral has been called sepiolite. Optical properties are: $N_m = 1.510 \pm .005$, extinction parallel to the fibers, biaxial negative, birefringence low. It is unattacked by HCl. N_m for sepiolite is 1.52 and for parasepiolite 1.506. This mineral has intermediate optical properties as well as composition.

The proximity of this occurrence to the chrysotile and deweylite suggests that the sepiolite represents an alteration product of these minerals.

In the following table (Table 1) the minerals are listed in alphabetical order. At the right, in vertical columns, are entered the names of the predominate rock types of this locality. The petrologic distribution and to some extent the relative frequency of occurrence and the relative importance in a rock is indicated, for each mineral, by an appropriate letter. This gives a general conception of the mineral associations.

The purpose of this table is to summarize, in a general way, much of the data on the minerals of this locality. For more detailed information on any mineral the reader is referred to a paper by Rogers¹⁵ in which a complete bibliography is given.

PARAGENESIS

The present record of the metamorphic history of the limestones shows no effect of the intrusion of hypersthene quartz diorite, the first member in the suite of intrusions which has altered these rocks. The spatial relations show that this intrusion was too far away to have had any effect other than recrystallization and fracturing resulting from heat and stresses produced during the injection of the magma.

The flow structure, so often found in the granodiorite near the contact with the sedimentaries, and the coarse crystallinity of the rock indicates that at the time of intrusion it was very viscous,

¹⁵ Rogers, A. F., Periclase from Crestmore, near Riverside, California, with a List of Minerals from this Locality: *Am. Mineral.*, vol. 14, pp. 12, 462-469, 1929.

and cooled slowly, likely under great pressure. Its contribution to the metamorphism of the limestone has been: (1) Recrystallization and further fracturing of the limestone. (2) The reduction of the carbonaceous material to graphite. (3) With a few exceptions the formation of the contact metamorphic minerals which are formed mostly under high pressure and temperature and without abundant mineralizers. This was accomplished in the following manner: (a) dissociation of magnesium carbonate to periclase; (b) by reaction in the impure limestone with the formation of spinel, magnetite, grossularite, wollastonite and diopside; (c) probably at a later stage chondrodite, wilkeite and phlogopite were formed by hydrous emanations from the magma containing phosphate, sulphate and halides. The hydration of the periclase to brucite took place, in part, during the cooling of this intrusion.

The contact metamorphic effects of the quartz monzonite porphyry were both endomorphic and exomorphic, but it is with the latter effects that we are principally concerned here, as the others have already been briefly discussed. As a consequence of this intrusion the limestones were further fractured and further recrystallized, especially near the borders of the dikes, until in some places the previous structures were eliminated. Chemical changes resulting from heat, pressure and the action of mineralizers were more general and more complex than those of the granodiorite. The most important of these changes from the standpoint of magnitude is the development of the garnetiferous contact rock. This development is particularly intense above the dikes where, we may assume, the action of the mineralizers would be concentrated. The total destruction in this mass of all previous structures and its coarse crystallinity indicates a complete reaction involving this material and slow cooling during subsequent recrystallization under rather uniform pressure. Thus by the solvent action on an impure limestone of the silicate solutions accompanying the quartz monzonite porphyry intrusion the formation of such minerals as grossularite, augite, diopside, diallage, wollastonite, scapolite, monticellite and bytownite-anorthite has been effected.

The manner in which the vesuvianite-calcite type of rock is confined to the outer margins of the contact mass suggests that its development was largely determined by physio-chemical relations in which a lower temperature and favorable concentrations in Al_2O_3 and SiO_2 were important factors.

TABLE 1

A—ACCESSORY MINERAL; C—COMMON; F—FREQUENT; M—CONSTITUENT MINERAL; R—RARE

MINERALS	OCCURRENCE															REMARKS	
	Hypersthene	Quartz	Diorite	Granodiorite	Enclaves in the Granodiorite	Quartz Monzonite Porphyry	Endomorphic Phases of Q. M. P.	Granite Porphyry	Pegmatite Dikes	Schists and Gneisses	Quartzites	Chino Quarry Limestone	Chino Quarry Quartzite	Sky Blue Quarry Limestone	Contact Rocks	Miscellaneous and Uncertain	
Albite.....									M								
Andesine.....	M			M		M				F	F						Alteration of galena
Anglesite.....															R	R	
Apatite.....	A	A	A	A	A	A	A	A	A	A	A	R	A	R	R		In wollastonite near contact
Apophyllite.....									R								In veinlets
Aragonite.....												F		F	F		
Arsenopyrite.....															R		
Augite.....				M		M	M			C	C		C		M		Associated with garnet
Axinite.....									R								Occurs as stains
Azurite.....															R		
Biotite.....	M	M	M			M	M	M	M	M			M				In cavities near contact
Bornite.....															R	R	Alteration of periclase
Brucite.....												C		C			In cavities near contact
Bytownite-Anorthite.....																R	
Calcite.....	F	F	F	F	F	F	F	F	F	F	M	F	M	M	M	C	Replaces quartz
Centrallasite.....									R								Alteration of galena
Cerussite.....																R	
Custerite.....															R	R	
Chalcedony.....															R	R	
Chalcocite.....															R	R	In cavities near contact
Chalcopyrite.....															R	R	In cavities near contact
Chlorite.....	C	C	C			C		C	C	C		C					Alteration of biotite
Chondrodite.....												C		C			Disseminated in predazzite
Chrysotile.....												R					Small masses near monz. dike
Clinocllore.....															R		
Clinzoisite.....															R		Small masses near contact
Crestmoreite.....															R		Disseminated in blue calcite
Datolite.....								R									Massive
Deweylite.....												R		R			Small masses near monz. dike
Diallage.....						M										M	
Diopside.....						M										M	
Epidote.....								C				R					
Foshagite.....															R		In veins cutting vesuvianite
Galena.....														R	R		
Gehlenite.....														R	R		Associated with merwinite
Graphite.....												C		C	C		Disseminated
Grossularite.....						M			R			C		C	M		
Greenockite.....															R		Coating sphalerite
Hematite.....	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	Alteration of iron minerals
Hornblende.....	M	M	M					C									
Hydromagnesite.....												R		R			Alteration of brucite
Hypersthene.....	M			M													
Jurupaite.....														R			In cavities in limestone

Similar silicate solutions operating outside of the garnet and the vesuvianite zones and therefore probably at lower temperatures were responsible for the formation of the associated rare minerals merwinite, gehlenite, and spurrite. The fine granular and the acicular wollastonite were also formed in the outer portion of the contact zone.

After the crystallization of the garnet and vesuvianite contact rocks and following the high temperature reactions, but in part contemporaneous with them, hydrous solutions containing phosphates, halides and sulphates found easy access into the limestones and contact rocks along the bedding planes and numerous fractures. This probably represented the latter part of the pneumatolitic stage or the early part of the hydrothermal stage. By their action on the limestones and on the previously formed contact rocks they formed various hydrated minerals. It is thought that from reactions of this type minerals such as epidote, clinozoisite, wilkeite, chondrodite and custerite were produced. By further cooling crestmorite, riversideite, foshagite, jurupaite and plazolite were formed. Crestmoreite, riversideite and foshagite are probably alterations of wilkeite.

Deweylite, chrysotile and sepiolite developed when the hydrothermal solutions acted probably on diopside and diallage or epidote of the contact zone. Xanthophyllite could have been formed either from preexisting silicates or from the impure limestone but under the conditions observed in the field it seems more probable that it too is an alteration of diopside or a closely related mineral. The reaction of the sulphated solutions on the spurrite resulted in thaumasite. Sulphide solutions deposited the sulphide minerals. It was in this stage of the hydrothermal action that the hydration of the periclase to brucite ended.

The metamorphic action of the pegmatite is similar in many respects to that of the quartz monzonite porphyry although not as intense and with the characteristic development of some borosilicate minerals. The first phase is characterized by the development in the pegmatite and in small adjacent contact zones of the common wollastonite, grossularite and the hydrous silicate epidote. This was followed shortly by apophyllite, prehnite, and the borosilicates, tourmaline, axinite and datolite. During the third stage apophyllite altered to okenite, prehnite to laumontite, and centralasite replaced quartz. Eakle¹⁶ mentions okenite as an alteration

product of wilkeite, but whether this alteration took place during the hydrothermal stage related to the quartz monzonite porphyry or during that same stage of the pegmatites is unknown.

Other reactions that have occurred here are entirely supergene. The iron bearing minerals have yielded hematite and limonite, galena has altered to cerrusite and anglesite, the copper minerals to azurite and malachite. Circulating waters have deposited secondary quartz, chalcedony, opal, secondary calcite and aragonite. Rogers¹⁷ described hydromagnesite as a supergene alteration product of brucite and deweylite as a supergene alteration of hydromagnesite.

SUMMARY

In recapitulating the results of these investigations the following points are emphasized:

Paleozoic(?) sandstones, shales and limestones have been intruded and recrystallized by a related series of pre-Cretaceous plutonic rocks in the order: hypersthene quartz diorite, granodiorite, quartz monzonite porphyry, granite porphyry and pegmatite dikes. Of these only the granodiorite, the quartz monzonite porphyry and the pegmatite dikes have been particularly effective metamorphic agents.

In the Crestmore quarries the principal effect of the granodiorite has been recrystallization and fusion. The more potent quartz monzonite developed large masses of contact rocks and most of the rare minerals found here. The action of the pegmatite has been similar but not as intense.

In the following the contact metamorphic minerals are listed below the rocks to which they owe their origin:

<i>Granodiorite</i>	<i>Qtz. Monzonite Porphyry</i>	<i>Pegmatites</i>
Graphite	Grossularite	Grossularite
Periclase	Augite	Wollastonite
Spinel	Diopside	Epidote
Magnetite	Diallage	Apophyllite
Grossularite	Wollastonite	Prehnite
Wollastonite	Scapolite	Tourmaline

¹⁶ Eakle, A. S., *op. cit.*, 1917. Jurupaite, a New Mineral: *Am. Mineral.*, vol. 6, pp. 107-109, 1921.

¹⁷ Rogers, A. F., An American Occurrence of Periclase and Its Bearing on the Origin and History of Calcite-Brucite Rocks: *Am. Jour. Sci.*, vol. 46, pp. 581-586, 1918.

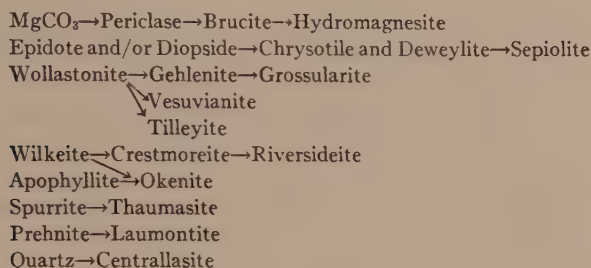
<i>Granodiorite</i>	<i>Qtz. Monzonite Porphyry</i>	<i>Pegmatites</i>
Diopside	Monticellite	Axinite
Chondrodite	Bytownite-Anorthite	Datolite
Wilkeite	Vesuvianite	Okenite
Phlogopite	Merwinite	Laumontite
Brucite	Gehlenite	Centrallasite
	Spurrite	
	Epidote	
	Clinozoisite	
	Wilkeite	
	Chondrodite	
	Custerite	
	Riversideite	
	Crestmoreite	
	Foshagite	
	Jurupaite	
	Plazolite	
	Deweylite	
	Chrysotile	
	Sepiolite	
	Xanthophyllite	
	Thaumasite	
	Sulphides	
	Brucite	

It should be evident from the preceding pages and the above lists that the reactions which took place during and following these intrusions were not simple and complete; they were characterized by their extreme complexity and recurrence. Thus it is that many minerals are polygenetic, not only in that they have been generated by each successive intrusion but they have been formed during the same intrusion by derivation from different parent minerals due to variations in concentration, pressure and temperature that must have prevailed in a mass of this type and size. Not only is polygenesis evident but one finds that the same minerals yield various alteration products. For example: wollastonite, a mineral common to each intrusion, occurs as four distinct morphic types (a fact in itself of genetic significance) but as shown by Dunham¹⁸ some of the alteration products of this mineral are tilleyite, gehlenite and vesuvianite. Gehlenite in turn yields grossularite. We know that all of the grossularite is not altered gehlenite and that all of the vesuvianite did not come from wol-

¹⁸ Dunham, K. C., A Note on the Texture of the Crestmore Contact Rocks: *Am. Mineral.*, vol. 18, pp. 11, 474, 1933.

lastonite. We are fairly certain of the intrusion which these reactions accompanied but not if they occurred during a later low temperature or a recurrent phase of the intrusion. These and many other questions can be answered only by further work.

The following graphically depicts some of the genetic sequences as they are known to date.



In studying the literature on Crestmore anent the paragenesis of the minerals occurring there one finds confusing and conflicting statements. Some authors do not distinguish between the different contact zones related to the various intrusions, the phases of each intrusion and in one case the nature of the injected rock has been incorrectly determined. In short, the tendency has been to too greatly simplify the facts and to regard the evidence of special cases as representative of the whole. If we are to more fully understand the contact metamorphic phenomena demonstrated here it is necessary to take a broader view. It is hoped that this paper will serve as a step in the right direction.

ADDITIONAL NOTES ON PSEUDOBROOKITE

CHARLES PALACHE, *Harvard University, Cambridge, Mass.*

Since the publication of my paper on this mineral¹ a number of new facts concerning it have come to my attention, which seem to be worthy of record.

In a paper which I overlooked, Dr. P. Ramdohr² has described minute crystals of pseudobrookite from a bore hole in altered basalt at Hessenbrücker Hammers, Hesse. The crystals show the forms: b , a , n , m , μ , e , l , q , and s of my list as well as two new forms, (212) described as common and (412) as rare. No measurements of these forms are given but they are stated to have been established by zonal relations. The position chosen is that of Groth-Dana, and the symbols as written above have been transformed to the new position adopted in my paper. Ramdohr also describes parallel growths of pseudobrookite on magnetite with $a(100)$ of the former parallel to a face of (111) of the latter and the c -axis (of our position) parallel to an edge of the octahedron.

Pseudobrookite has long been known from the nepheline rock (shonkinite) of the Katzenbuckel in Baden. In a highly altered zone in one of the newer quarries there, minute crystals of pseudobrookite are numerous associated with secondary phosphate minerals. One of these crystals, not more than 0.1 mm. in length but very brilliant, was measured by Dr. Pough and showed the forms: $b(010)$, $a(100)$, $m(110)$, $\mu(210)$, $e(101)$, $q(111)$, $s(121)$, and $r(212)$. The last-named form, first found by Ramdohr as noted above, is thus confirmed.

Mr. Lazard Cahn has drawn my attention to parallel growths which were found in the lot of pseudobrookite described in my first paper. One of the specimens which he sent me consisted of pseudobrookite needles attached to the surface of the basal plane of a hematite crystal. The c -axes of the needles were inclined about 41° to the vertical axis of the hematite and attached in such a manner that the plane of contact with the hematite is approximately the pyramid (121) of pseudobrookite. Furthermore, the c -axis of the latter is normal to a face of (11 $\bar{2}$ 3) of hematite.

In the fall of 1934 a new and remarkable occurrence of pseudobrookite crystals of hitherto unknown perfection was discovered

¹ *Am. Mineral.*, vol. 19, p. 16, 1934.

² *Notizblatt des Vereins f. Erdkunde, Hessische Geolog. Landesanstalt*, 1923.

in the Thomas Range, Utah, by Messrs. E. Over, Jr., and A. Montgomery. The new locality is on the east side of the range near Joy, Juab County. The specimens acquired by the Harvard Mineralogical Museum are in the usual white lithophysal rhyolite, some of the flattened cavities being as much as 4 cm. in diameter. The pseudobrookite needles are implanted on the walls as radiating groups or in sheaflike bundles. The longest needle is $2\frac{1}{2}$ cm. long with a flat cross-section of about $.1 \times .25$ mm. Others are much more slender, like millerite needles. Unless the needles span the cavity from wall to wall their free ends are sharply terminated. In the sheafs the crystals are short and much stouter, with diameters reaching .5 to .75 mm. They are sometimes doubly terminated. Excellent measurements were obtained which were in substantial agreement with the angles based on the elements of the earlier paper. Three new forms were found in addition to all those earlier observed. The position angles for these forms measured and calculated, as well as those calculated for the two found by Ramdohr, are given in the following table, which may be regarded as a supplement to that already published.

PSEUDOBROOKITE. ANGLE-TABLE

		Measured		No. of faces	Calculated	
		ϕ	ρ		ϕ	ρ
<i>x</i>	021	0°05'	36°56'	2	0°00'	36°42'
<i>w</i>	252	22 08	45 08	3	22 15	45 11½
<i>v</i>	141	14 25	57 09	3	14 20½	56 59
<i>r</i>	212	—	—	—	63 57	22 59½
<i>t</i>	412	—	—	—	76 16	38 07½

The crystals of pseudobrookite are always deeply striated longitudinally. They have a brilliant metallic lustre and the groups of shining needles make very attractive micromounts. The drawings show the new forms and the wide range of habit. They were made by Mr. C. W. Wolfe.

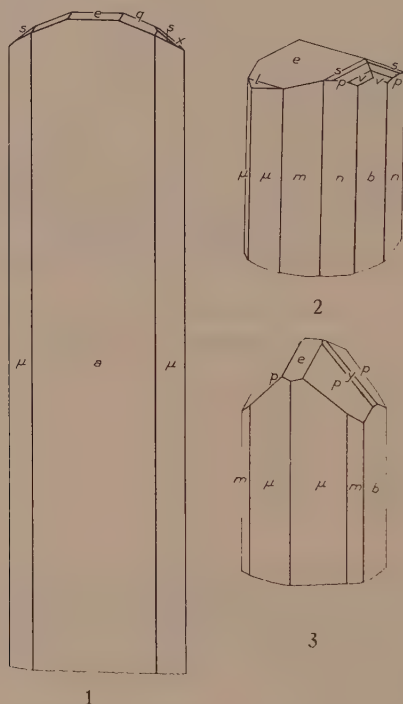
CHEMICAL COMPOSITION: No positive conclusion as to the correct formula of pseudobrookite has been hitherto reached. The simplest formula proposed is Fe_2TiO_5 first derived by Doss³ for an artificial product. Pauling's⁴ structure study led to the same result. The excess of TiO_2 , found in most analyses, over that called for by

³ *Zeit. f. Kryst.*, vol. 20, p. 574, 1892.

⁴ *Zeit. f. Kryst.*, vol. 73, p. 102, 1930.

this formula was explained by Pauling as due to the presence of rutile in minute intergrown particles. He found in his powder photographs lines which did not belong to the pseudobrookite structure but which were completely explained by reference to rutile.

To check this interpretation, Messrs. Berman and Dane polished a crystal of pseudobrookite and examined the surface by reflected light with high magnification. They could perceive a small amount of foreign material as vague bands in the crystal but were not able to determine its nature.



FIGS. 1-3. Crystals of pseudobrookite from Thomas Mts., Utah, showing the forms: $a(100)$, $b(010)$, $n(120)$, $m(110)$, $\mu(210)$, $e(101)$, $l(301)$, $\gamma(031)$, $x(021)^*$, $q(111)$, $s(121)$, $p(131)$, and $v(141)^*$.

The following analysis, made on 0.28 grams of the Thomas Mts. pseudobrookite, shows a much nearer approach to the formula Fe_2TiO_5 than any yet made of the naturally occurring mineral. It was made on crystal fragments quite free from any visible im-

purity. The figures indicate an excess of TiO_2 (rutile ?) of approximately 4%. It seems a satisfactory confirmation of the simple formula for pseudobrookite and of the explanation of the common high content of TiO_2 as due to enclosed rutile.

COMPOSITION OF PSEUDOBROOKITE

	1.	2.
Fe_2O_3	60.57	66.64
TiO_2	38.12	33.36
MgO	1.26	—
	<hr/> 99.95	<hr/> 100.00

1. Thomas Mts. F. A. Gonyer, analyst.
2. Theoretical values for Fe_2TiO_5 .

AUGELITE FROM MONO COUNTY, CALIFORNIA

DWIGHT M. LEMMON, *Stanford University, California.*

Augelite, basic aluminum phosphate, was discovered in the andalusite orebody of the Mono County Mine of Champion Silimanite, Inc., during the summer of 1934 by the writer while engaged in a field study of the geology and mineralogy of the deposit, and was subsequently identified in the mineralogy laboratory at Stanford University. The andalusite mine is located on the west slope of White Mountain in California, and was briefly described by P. F. Kerr¹ in 1932.

DESCRIPTION OF MONO COUNTY AUGELITE

The augelite occurs in white, colorless, to yellowish cleavable masses. In the largest specimen found individual cleavages can be traced for over two inches although part of this distance represents an intergrowth of augelite with other minerals; other specimens are smaller, grading down to microscopic dimensions. The luster is vitreous. Cleavage is perfect parallel to the prism $m\{110\}$ in two directions at angles of about 67° and 113° , and less perfect in a third direction parallel to the dome $x\{101\}$ at an angle of $77\frac{1}{2}^\circ$ to the prism. Figure 1 shows the plan and clinographic projection of a cleavable mass of augelite. In constructing the clinographic projection, the plan has been rotated through the customary angle, $18^\circ 26'$; the unusual foreshortening of the prism face is caused by the fact that in the axial ratio of augelite, a is greater than b .

Cleavage angles of augelite from this new locality measured on the reflection goniometer average for the prism cleavage $mm(110 \wedge \bar{1}10)$ $66^\circ 57'$ as compared with the value of $66^\circ 46'$ recorded by Prior and Spencer;² for the angle between the prism and dome $mx(110 \wedge 101)$, $77^\circ 43'$ as compared with the recorded value of $77^\circ 35'$. Measurements on the poorer domal cleavage vary $\pm \frac{1}{2}^\circ$ from recorded values because of poorer reflections, but those on the perfect prism cleavage are relatively constant and differ from previously recorded values by only 11 minutes. The domal cleavage is generally not prominent in hand specimens.

¹ Kerr, P. F., The occurrence of andalusite and related minerals at White Mountain, California: *Econ. Geol.*, vol. 27, pp. 614-642, 1932.

² Prior, G. T., and Spencer, L. J., Augelite: *Mineral. Mag.*, vol 11, pp. 16-23, 1895.

Hardness of the Mono County mineral is about 5. Optical properties agree very closely with those given by Prior and Spencer for Bolivian augelite. Chemical tests prove the mineral to be an aluminum phosphate. The mineral is infusible, and water is given off when it is heated in the closed tube. A determination

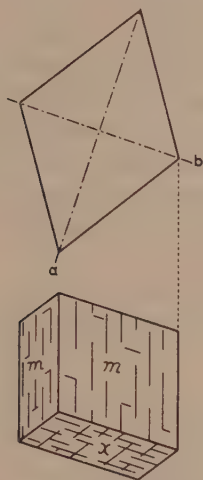


FIG. 1. Plan and clinographic projection of augelite cleavages $m\{110\}$ and $x\{101\}$.

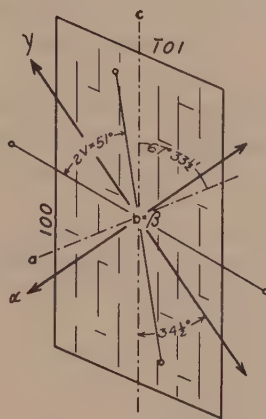


FIG. 2. Optical orientation diagram of augelite. Section parallel to $\{010\}$.

of the water content by the Penfield method gave a value of 12.23% compared with the theoretical value of 13.51%. Only 0.17 gram augelite was used in this determination, and this material may have contained impurities; so the result checks as closely as can be expected.

The specific gravity of larger masses of the augelite is high because of an admixture of intergrown minerals. Determination of the specific gravity by the pycnometer method, using small, pure fragments of the augelite carefully sorted under a hand lens, gave a value of 2.67, slightly less than the published value of 2.696 given for Bolivian augelite. Amount of material used was 0.9289 gram.

The extinction angle is $34\frac{1}{2}^\circ$ in the obtuse angle measured on an oriented section cut parallel to $b(010)$ (see orientation diagram, Fig. 2). Indices, determined by immersion in index liquids using light passed through a Wratten E22 filter, vary only one or two figures in the third place from those found by Prior and Spencer

using the prism method. Fragments showing an optic axis figure were used in determining n_β . The axial angle $2V$ was computed from $2E$, obtained by measuring the distance between the isogyres of an interference figure in an oriented section cut perpendicular to the acute bisectrix. Some cleavage fragments show the emergence of an optic axis just beyond the field of view.

No euhedral crystals have been found at this new locality, but careful examination of mining operations may lead to their discovery. Only a small number of specimens of the massive material have been found, but further search of the dumps and of operating faces is expected to reveal others. The mineral has been mistaken for barite by the ore sorters, and it also greatly resembles feldspar; both of the latter minerals would be discarded in sorting andalusite ore.

The following tabulation summarizes the properties of Mono County augelite as compared with data from Prior and Spencer for Bolivian augelite:

MACHACAMARCA, BOLIVIA	MONO COUNTY, CALIFORNIA
Crystals of the monoclinic prismatic class	Massive
Cleavage in 3 directions	Cleavage in 3 directions
mm $(110 \wedge \bar{1}10) 66^\circ 46'$	mm $66^\circ 57'$
mx $(110 \wedge \bar{1}01) 77^\circ 35'$	mx $77^\circ 43'$
H. 4.5 to 5	H. 5
Density 2.696	Sp. Gr. 2.67
Chemical composition	Qualitative tests for Al, PO_4 , H_2O
$AlPO_4 \cdot Al(OH)_3$ (13.51% water)	(12.23% water by Penfield method)
Biaxial negative	Biaxial negative
$2V = 51^\circ$	$2V = 52^\circ$
$c \wedge \gamma = 34^\circ$	$c \wedge \gamma = 34\frac{1}{2}^\circ$
$n_\gamma = 1.588$	$n_\gamma = 1.587 \pm .001$
$n_\beta = 1.576$	$n_\beta = 1.575 \pm .001$
$n_\alpha = 1.574$	$n_\alpha = 1.572 \pm .001$
Birefringence .014	Birefringence .015 \pm .002

Since properties of Machacamamarca augelite agree so closely with those of the Mono County mineral, there can be no doubt that the two minerals are the same.

MODE OF OCCURRENCE

Augelite in the Mono County Mine of Champion Sillimanite Inc., occurs as a hydrothermal mineral deposited from the widespread hydrothermal solutions that acted upon the andalusite de-

posit subsequent to the formation of andalusite, corundum, diaspore, topaz, and other minerals of the pyrometasomatic stage of the deposit. The augelite is directly associated and intergrown with lazulite, rutile, barite, pyrophyllite, muscovite, alunite, and quartz, and the same hand specimens show residual andalusite and corundum.

In some specimens a yellow-brown, dull alteration product has formed in the augelite. This material seen in thin section penetrates the augelite along cleavages, and to a lesser extent cuts across the cleavage. The mineral is a gray color in thin section, has an aggregate structure, high double refraction, and very high relief. Its aggregate character and scarcity prevent its identification.

OTHER OCCURRENCES OF AUGELITE

Augelite was first named and described from the iron mine of Westanå, Skåne, Sweden, in 1868 by C. W. Blomstrand.³ His material was massive without euhedral crystals, and no geometrical or optical properties were listed. In the same article Blomstrand also named from the Westanå locality three other aluminum phosphate minerals: berlinite, trolleite, and attacolite. Only augelite has been substantiated by discovery of crystalline material in other localities, and the other three are still regarded as indefinite or doubtful species. Hintze⁴ lists trolleite as a definite species, and cites Blomstrand's original data, but does not mention berlinite or attacolite.

Augelite was not fully substantiated as a new species until 1895 when Prior and Spencer described small, euhedral, monoclinic crystals of augelite from Machacamarca, Bolivia. The augelite occurred associated with bournonite and octahedral pyrite.

The mineral has subsequently been reported from three other Bolivian localities: Tatasi,⁵ Portugalete,⁵ and Oruro.⁶ Associated minerals in the silver mines of Tatasi are pyrite, siderite, gypsum, calcite, pyrophyllite, kaolin, and sphalerite in the jamesonite "feather" ore. The specimens from Oruro showed a mass of auge-

³ Blomstrand, C. W., *Öfversigt af K. Vet. Akad. Förhändlinger, Stockholm*: vol. 25, p. 199, 1868. (Article not seen.)

⁴ Hintze, C., *Handbuch der Mineralogie, Erster Band*, 1933.

⁵ Spencer, L. J., Augelite from Tatasi and Portugalete, Bolivia: *Mineral. Mag.*, vol. 12, pp. 1-5, 1898.

⁶ Spencer, L. J., Augelite from Oruro, Bolivia: *Mineral. Mag.*, vol. 14, pp. 323, 1907.

lite, arsenopyrite, quartz, pyrite, and stannite crystals coating a matrix of massive quartz, pyrite, and tetrahedrite. Spencer points out that augelite may not be as rare a mineral in Bolivia as has previously appeared, for augelite crystals greatly resemble barite in form, and can be distinguished only by measurement of crystal angles, cleavage, or optical properties.

The original Swedish discovery and the Bolivian localities make five previously known occurrences of augelite. This note records the first discovery of augelite in North America, and also shows a mineral association entirely different from previous occurrences.

The writer gratefully acknowledges the assistance of Dr. A. F. Rogers in the preparation of this paper, which is published by permission of Mr. C. D. Woodhouse, General Manager, Champion Sillimanite, Inc.

NOTES AND NEWS

A METHOD FOR REMOVING IRON OXIDE COATINGS FROM MINERALS¹

M. DROSDOFF AND E. TRUOG, *University of Wisconsin, Madison, Wisconsin.*

This paper deals with a method for removing the iron oxide coating which is often found on the surface of finely divided uncrushed mineral grains of sedimentary materials. These coatings render petrographic studies more difficult and less accurate, lead to the contamination of x -ray patterns, and interfere with accurate specific gravity determinations and separations, especially in the case of the more finely divided materials. Acids have been used for the removal of this ferric oxide, but the concentration necessary is so great that in many cases minerals other than the ferric oxide are seriously attacked. The writers found, in attempting to remove ferric oxide from soil colloids, that, by introducing hydrogen sulfide into a water suspension of the colloid, the free ferric oxide is quickly changed to iron sulfides which dissolve readily in dilute HCl. The simplicity and effectiveness of the method led to its application in the field of pure mineralogy.

A review of the literature shows that hydrated ferric oxide has been used for more than sixty years as an absorbent for H_2S in the purification of coal gas. Wright,² in 1883, reported that $Fe(OH)_3$ suspended in water turned black when H_2S was introduced, Fe_2S_3 , FeS , and S being formed. Allen et al.³ showed that these iron sulfides are completely soluble in cold dilute HCl. Recently, Pearson and Robinson⁴ summarized the literature and concluded that a mixture of sulfides is formed.

ACTION OF HYDROGEN SULFIDE ON IRON OXIDE

Preliminary tests with H_2S -saturated water suspensions of 100-mesh limonite showed rapid formation of black iron sulfides which

¹ Published with the permission of the Director of the Wisconsin Agricultural Experiment Station. This work was supported in part by a grant from the Wisconsin Alumni Research Foundation.

² Wright, L. T., Some Notes on Hydrated Ferric Oxide and Its Behavior with Hydrogen Sulfide: *Jour. Chem. Soc.*, vol. 43T, pp. 156-163, 1883.

³ Allen, E. T., Crenshaw, J. L., Johnston, J., and Larsen, E. S., Mineral Sulfides of Iron: *Amer. Jour. Sci.*, (4) vol. 33, pp. 169-236, 1912.

⁴ Pearson, T. G., and Robinson, P. L., The Reaction between Monohydrated Ferric Oxide and Hydrogen Sulfide at 100° : *Jour. Chem. Soc.*, pp. 814-823, 1928.

dissolved readily in cold 0.05 *N* HCl. Most of the original iron oxide was dissolved by this treatment. To determine whether or not the acidity of the H₂S solution (about pH 4, slightly less acid than carbonated water) dissolved the iron oxide before it was changed to sulfides, the H₂S solution was neutralized with NH₄OH before being used. This neutralized H₂S solution was even more effective than the acid H₂S solution, which indicated that the sulfides are formed directly as a result of a surface reaction.

In further tests, samples (50 mg. each) of finely powdered limonite and hematite were shaken with 200 cc. of H₂S-saturated water adjusted to pH 7 with NH₄OH. The iron sulfides formed were dissolved in 0.05 *N* HCl and the iron in solution determined. Shaking for one-half hour with subsequent HCl treatment dissolved 90% of the limonite but only 8.5% of the hematite. After one hour of shaking, all of the limonite dissolved but only 9% of the hematite, indicating that the amount of surface exposed by the crystalline hematite was not sufficient for rapid action of the H₂S.

Samples of crystalline hematite and goethite and ordinary limonite were then prepared in which the particle size was 0.0001 mm. and less in diameter. The goethite and hematite were ground in a tool steel ball mill. Suspensions containing 50 mg. of these materials in 200 cc. of H₂S-saturated water adjusted to pH 7 with NH₄OH were shaken for one-half hour. The iron sulfides formed were dissolved in cold 0.05 *N* HCl, the solution filtered and the iron determined in the filtrate. In the case of goethite and limonite all of the material had dissolved, but in the case of the hematite 7% of the sample remained undissolved. Upon analysis, 40% of this residue was found to consist of SiO₂, indicating the presence of an iron silicate, the iron of which did not react readily with the H₂S. These tests show that iron oxide, hydrated and unhydrated, when sufficiently finely divided reacts quickly with H₂S to form sulfides which are readily soluble in 0.05 *N* HCl.

ACTION OF HYDROGEN SULFIDE ON IRON IN ROCKS AND MINERALS

In order to find out if the H₂S treatment would have an appreciable effect on ferric iron as found in igneous rocks and especially in silicate form, 0.1 gram samples of biotite and basalt and a 0.2

gram sample of granite, all ground finer than 100-mesh, were shaken for several hours with 300 cc. of H_2S -saturated water solution adjusted to pH 7 with NH_4OH . At various intervals, 10 cc. portions of the suspensions were removed and treated with 10 cc. of 0.1 N HCl and then filtered quickly. After expelling the H_2S and oxidizing with ammonium persulfate, the filtrates were tested for iron colorimetrically with KCNS . Check samples of the mineral powders were treated with water alone instead of the H_2S solution. Samples of these suspensions were treated with HCl , filtered, and tested in exactly the same way as the others. It was found that the H_2S treated samples gave only a slight test for iron, the same as the check samples, indicating that what little solution of iron took place was due to the direct action of the HCl on the original minerals, and that the H_2S treatment does not readily affect iron in the silicate form.

DETAILS OF PROCEDURE FOR REMOVING FERRIC OXIDE

Place a one to ten gram sample of the powdered mineral in a 500 cc. Erlenmeyer flask with 200 to 300 cc. of distilled water. Saturate the suspension with hydrogen sulfide which is bubbled in from a tank or generator. This takes about 10 or 15 minutes. Quickly add about 5 cc. of N NH_4OH and stopper immediately with a rubber stopper. Shake with a mechanical shaker for about an hour, or intermittently by hand for a somewhat longer period. Acidify with 0.1 N HCl , adding an excess of about 50 cc. so as to completely dissolve the iron sulfides. Filter immediately so as to avoid action of the acid on the other minerals. Wash several times with 0.05 N HCl . If desired, the amount of free iron oxide removed may be determined by an analysis of the filtrate and washings. The mineral residue on the filter paper is always contaminated with free sulfur which may be removed in the following way: Wash twice with 95% ethyl alcohol to remove water, then three times with a solution consisting of one volume of carbon bisulfide and two volumes of 95% alcohol to remove the sulfur, and finally twice with the alcohol to remove the carbon bisulfide.

The residue is then dried, thus completing the cleaning process. In place of filtering and washing on a filter paper, this portion of the procedure may often be conveniently performed by washing by decantation using a centrifuge if necessary.

CONFIRMATORY TESTS WITH THE PROCEDURE

In order to check the method further, samples⁵ of feldspar, baddeleyite, and quartz powder, the surfaces of which were coated with considerable iron oxide as revealed under the microscope, were subjected to the hydrogen sulfide treatment. After the treatment, the minerals, under the microscope, appeared relatively free of iron oxide but otherwise were unaffected. An appreciable amount of iron was found in the extracts, but distinct tests for other constituents were not obtained. This showed that the iron oxide coatings had been removed without noticeably affecting the minerals in question.

Two samples of sandstone powder⁶ which contained some feldspar and the heavy minerals—zircon, tourmaline, and apatite—were given the hydrogen sulfide treatment. There had been difficulty in making specific gravity separations of these rock powders, because the iron oxide coating on the feldspar and quartz grains increased their specific gravity so much that they would not separate sharply from the heavy minerals. It was not permissible to use strong acids to remove this coating because of the solubility of the apatite and feldspar. After the hydrogen sulfide treatment, however, the quartz and feldspar were easily separated from the heavy minerals and, upon microscopic examination, were found to be practically free of iron oxide.

Since apatite is one of the easily soluble minerals encountered in making specific gravity separations, it seemed desirable to determine just how much it is affected by the hydrogen sulfide treatment. Accordingly, a known amount of 100-mesh apatite was added to a sample of sandstone powder, which was then given the hydrogen sulfide treatment. After this treatment, a specific gravity separation was made and practically all of the apatite was recovered. The hydrogen sulfide extract contained an appreciable amount of iron but only a trace of calcium, showing that the apatite had hardly been attacked at all. A microscopic examination of the treated apatite showed very little if any rounding of the crystal fragments when compared with an untreated sample.

The presence of free iron oxide may also obscure correlations between the results of chemical analysis and optical determina-

⁵ Samples furnished by Dr. R. C. Emmons, Department of Geology.

⁶ Acknowledgment is due to Mr. Tyler and Mr. Marsden of the Department of Geology for furnishing the samples and giving information regarding them.

tions of minerals. It is desirable to distinguish between free iron oxide and combined iron, since the latter affects the refractive index of a mineral. In some work⁷ on the correlation between the optical properties and chemical composition of different varieties of supposedly pure muscovite, treatment with hydrogen sulfide removed 0.3 to 1.5% of free iron oxide. After this treatment, a better correlation was obtained between the refractive index and chemical composition of the muscovites. The hydrogen sulfide treatment can probably be used to advantage in similar investigations of many other minerals.

Hematite, unless extremely finely divided, is not readily affected by the hydrogen sulfide treatment. A sample of feldspar containing relatively coarse crystals of hematite was treated with hydrogen sulfide, but not much of the free iron oxide was removed. The method, while well adapted for the removal of finely divided iron oxide, is not suitable for the removal of the larger crystals. These may be removed by specific gravity separation.

SUMMARY

It was found that the iron oxide coating of minerals can be easily removed if a water suspension of the minerals is first treated with hydrogen sulfide. This treatment changes the finely divided iron oxide to iron sulfides which dissolve quickly in 0.05 *N* hydrochloric acid. Other minerals such as silicates and apatite are not appreciably affected, although carbonates would be. The method has much useful application in optical and specific gravity investigations of minerals.

⁷ Work by Garth Volk in the Departments of Geology and Soils, University of Wisconsin.

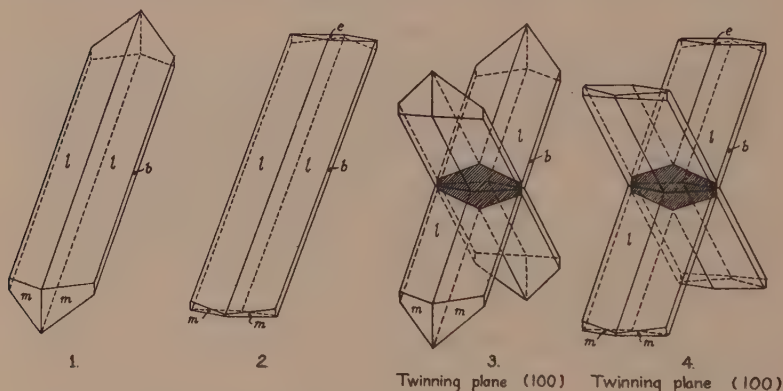
GYPSUM CRYSTALS FROM ALFALFA COUNTY, OKLAHOMA

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The gypsum crystals described in this article were found in Sec. 36, T. 26 N., R. 10 W., in the Salt Plains of Alfalfa County, Oklahoma. They were presented to the writer for identification by Dr. Ralph Bird.

The Salt Plains is a saline marsh, of approximately sixty square miles, in the central part of the county. The floor of the plain is composed of silt and fine sand, covered with a thin layer of salt crystals. The salt crust has been formed by the evaporation of saline solutions, which probably obtained their constituents from the underground salt beds of the Enid formation (Permian).

A few scattered gypsum crystals are found in the salt layer. These crystals vary in length from one-half to two inches and have a brown color, due to impurities of iron oxides.



The gypsum has four distinct crystal habits, namely:

1. Crystals with well developed $l(111)$ and smaller $e(\bar{1}03)$ and $b(010)$ forms. Fig. 2.
2. Crystals with well developed $l(111)$ and small $m(110)$ and $b(010)$ forms. Fig. 1.
3. Penetration twins of the $l(111)$, $e(\bar{1}03)$ and $b(010)$ habit; twinning plane (100). Fig. 4.
4. Penetration twins of the $l(111)$, $m(110)$ and $b(010)$ habit; twinning plane (100). Fig. 3.

BOOK REVIEW

SPEZIELLE PETROGRAPHIE DER ERUPTIVGESTEINE, EIN NOMENKLATUR-KOMPENDIUM IN AUFTRAGE DER DEUTSCHEN MINERALOGISCHEN GESELLSCHAFT. W. EHRENREICH TRÖGER. 360+V pages. Price bound, 20 RM. Deutschen Mineralogischen Gesellschaft e.V., Berlin W 35, 1935.

Many American petrographers will be gratified to learn from this book that German as well as American petrographers are trying to work out a system of rock classification that will be quantitative, and at the same time not too elaborate and that will involve as few changes from the Rosenbusch classification and nomenclature as possible. I, for one, hope that it is not looking for the millenium to expect in the near future a general agreement among petrographers the world over on some relatively simple quantitative rock classification. Perhaps the time is not quite here but may petrographers soon get together and agree on some scheme of classification.

The author divides rocks into 32 families following the usual scheme but giving quantitative limits as shown in the following table:

	ALKALI FELDSPAR	ALKALI FELDSPAR +PLAGIOCLASE	PLAGIOCLASE	ALMOST LACKING FELDSPAR
<i>Quartz</i>	Aplite granite (hololeucocratic)	Alkali-lime granite (orth. \geq plag.)	Quartz diorite	Peracidite (hololeucocratic)
	Alkali granite (leucocratic mesotype)	Granodiorite (orth. < plag.)		
<i>Neither quartz nor foids</i>	Aplosyenite (hololeucocratic)	Lime-alkali syenite (orth. > plag.)	Anorthosite (hololeucocratic) Diorite (an < 50) Gabbro-diorite (an = 50) Gabbro (an > 50)	Pyroxenite Amphibolite Garnetite Micaite Peridotite Melalitolite Silikotelite
	Alkali syenite (leucocratic)	Monzonite (orth. = plag.)		
	Lusitanite (melanocratic mesotype)	Mangerite (orth. < plag.)	Tilaite (melanocratic)	
<i>Foids</i>	Nepheline syenite (holo- or leucocratic)	Theralite (orth. \geq plag.)	Essexite (plag. \pm > orth.)	Fergusite (leucite) Ijolite (nepheline) Tawite (sodalite) Turjaite (melilite + foids)
	Shonkinite (melanocratic mesotype)			

The main part of the book is taken up with brief descriptions of all the rock names that have been proposed. These are arranged under the families to which they belong. The descriptions give references to the original or chief literature and for the most part follow the original description. They give the original locality or a typical example of occurrence, the magma provinces in which this rock is found—Atlantic, Pacific, or Mediterranean—, the quantitative mineral composition of type material, a chemical analysis where available, the position in Niggli's and the C. P. I. W. systems, synonyms, and varieties. Many new Rosival estimates of the mineral composition were made by the author.

At the end a list of synonyms and doubtful species is arranged alphabetically. An index enables one to locate any name in the text. A table for determining the position of a rock is given, a table of Niggli's magma types, and tables of analyses of minerals from various rocks.

The author seems to favor the rather haphazard method used in the past in naming rocks in which an endless number of names can be proposed for rocks with textural, mineral, or other differences. Any experienced field geologist knows that in any large area of igneous rocks there is likely to be a large variety of rocks, as each intrusive and many of the extrusives will have some peculiarities. Is it not better, as many American petrologists believe, to have a rather simple, quantitative rock classification, and to bring out these special differences by the use of mineral, textural, or other modifiers in a systematic way, and to indicate the special rock type by a formation name just as stratigraphers do? Our subdivisions are arbitrary—why carry on the refinement to the point where a knowledge of the nomenclature is a burden and few workers find it worth while to learn all the lingo? In other sciences the divisions may be more natural and hence necessary. Too much elaboration in nomenclature may retard progress. I speak with feeling, as I have a poor memory for such things.

The material of the book under review is well and carefully prepared. American petrographers would not agree to all the details. Tröger uses *theralite* for the family with essential plagioclase, orthoclase, and nepheline, and *essexite* for the similar rocks lacking essential orthoclase. Americans would replace his *essexite* by *theralite* and would use *essexite* or perhaps some other name in place of *theralite*.

The book should prove constantly useful to all workers in petrography. The material is very well arranged for practical use and the data are surprisingly complete and quantitative, considering the small space available for each rock name. As is common for all German books, the price is excessive and this will no doubt reduce its use in this country.

ESPER S. LARSEN

NOMINATIONS FOR OFFICERS OF THE MINERALOGICAL
SOCIETY OF AMERICA FOR 1936

The Council has nominated the following for officers of *The Mineralogical Society of America* for the year 1936:

PRESIDENT: W. S. Bayley, Dept. of Geology, University of Illinois, Urbana, Illinois.

VICE-PRESIDENT: H. L. Alling, 31 Barrington Street, Rochester, New York.

SECRETARY: Paul F. Kerr, Dept. of Geology and Mineralogy, Columbia University, New York, New York.

TREASURER: Waldemar T. Schaller, United States Geological Survey, Department of the Interior, Washington, D.C.

EDITOR: Walter F. Hunt, University of Michigan, Ann Arbor, Michigan.

COUNCILOR (1936-1939): A. F. Buddington, Princeton University, Princeton, New Jersey.

The sixteenth annual meeting of the Society will be held at the Waldorf Astoria Hotel, December 27th-29th, 1935, in New York City. It is planned to publish in the December issue of the Journal a *preliminary* list of titles of papers to be presented before the Society at its annual meeting. In order to appear on the advance program, titles of papers should be in the hands of the Secretary by *November 10th*.

A program containing abstracts of all papers will be printed for distribution at the annual meeting. Abstracts for this program should be in the hands of the Secretary by *November 25th*.

PAUL F. KERR, *Secretary*

NEW MINERAL NAMES

Todorokite

YOSHIMURA, TOYOFUMI: "Todorokite," a New Manganese Mineral from the Todoroki Mine, Hokkaido, Japan. *Jour. Faculty of Science, Hokkaido Imp. Univ., Ser. IV, Geol. and Min.*, 2, No. 4, 289-297, 1934, 2 pls. (In English).

NAME: From the locality, the Todoroki Mine.

CHEMICAL PROPERTIES: A hydrated oxide of manganese; $2(\text{RO} \cdot \text{MnO}_2 \cdot 2\text{H}_2\text{O}) \cdot 3(\text{Mn}_2\text{O}_3 \cdot 3\text{MnO}_2 \cdot 2\text{H}_2\text{O})$. Analysis: K_2O 0.54, Na_2O 0.21, MgO 1.01, CaO 3.28, BaO 2.05, Al_2O_3 0.28, Fe_2O_3 0.20, MnO 65.89, O 12.07, $\text{H}_2\text{O} +$ 9.72, $\text{H}_2\text{O} -$ 1.56, SiO_2 0.45, TiO_2 tr., CO_2 tr., P_2O_5 0.42, SO_3 0.28, Insol. 1.28; total 99.24.

BLOWPIPE PROPERTIES: Turns brown, loses its metallic luster but does not fuse. Soluble in HCl with evolution of chlorine, in concentrated H_2SO_4 to distinctly purple red solution, in HNO_3 with residue of MnO_2 .

CRYSTALLOGRAPHICAL PROPERTIES: Monoclinic (?), $\beta = 110^\circ$. Twinning frequent. Cleavage (010) and (100), highly perfect. X-ray examination indicates crystallinity.

PHYSICAL AND OPTICAL PROPERTIES: Color and luster like graphite. Under the microscope the mineral is transparent, with various shades of brown color and shows parallel extinction. Plane of optic axes appears to be parallel to (010). n greater than 1.74, birefringence nearly 0.02. Pleochroism distinct,

Z = yellowish brown, X = dark brown. $Z > X$.

Soft, soils the fingers. G. 3.67.

OCCURRENCE: Found as very fine fibrous flakes, about 0.05 mm. in length, loosely aggregated in sponge like masses, in druses in the Todoroki Mine, 25 kms. S.E. of Ginzan, Siribesi Province, Hokkaido, Japan. Derived from inesite and an inesite-like zeolite, in auriferous quartz veins.

W. F. F.

Milowite

WILSON, J. N.: Milowite, an unusual form of silica. *Sands, Clays, and Minerals*, Vol. 2, No. 3, 127-130, 1935.

A trade name for a very fine grained chalk-like form of quartz occurring in large quantities on the Island of Milos, Grecian Archipelago. SiO_2 97.86%.

W. F. F.

Blockite Ahlfeldite

RAMDOHR: Zwei neue Mineralien. *Centr. Min.*, Abt. A, No. 6, p. 189, 1935.

Blockite is a nickel selenide, probably NiSe_2 . Ahlfeldite a complex nickel selenate. From Colquechaca.

W. F. F.